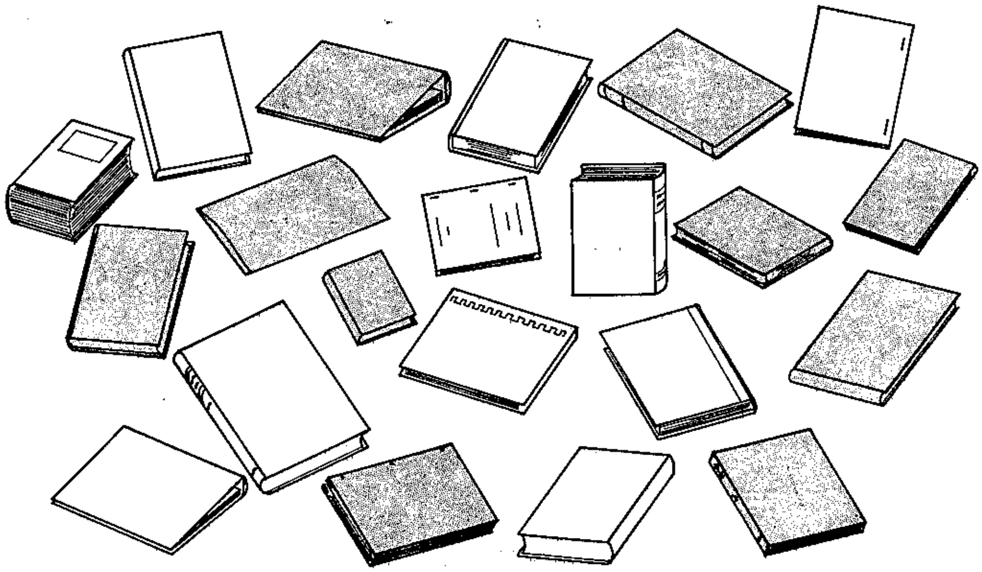
LIME-SOIL STABILIZATION STUDY
a selected literature review



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STATE OF CALIFORNIA

TRANSPORTATION AGENCY

DEPARTMENT OF PUBLIC WORKS

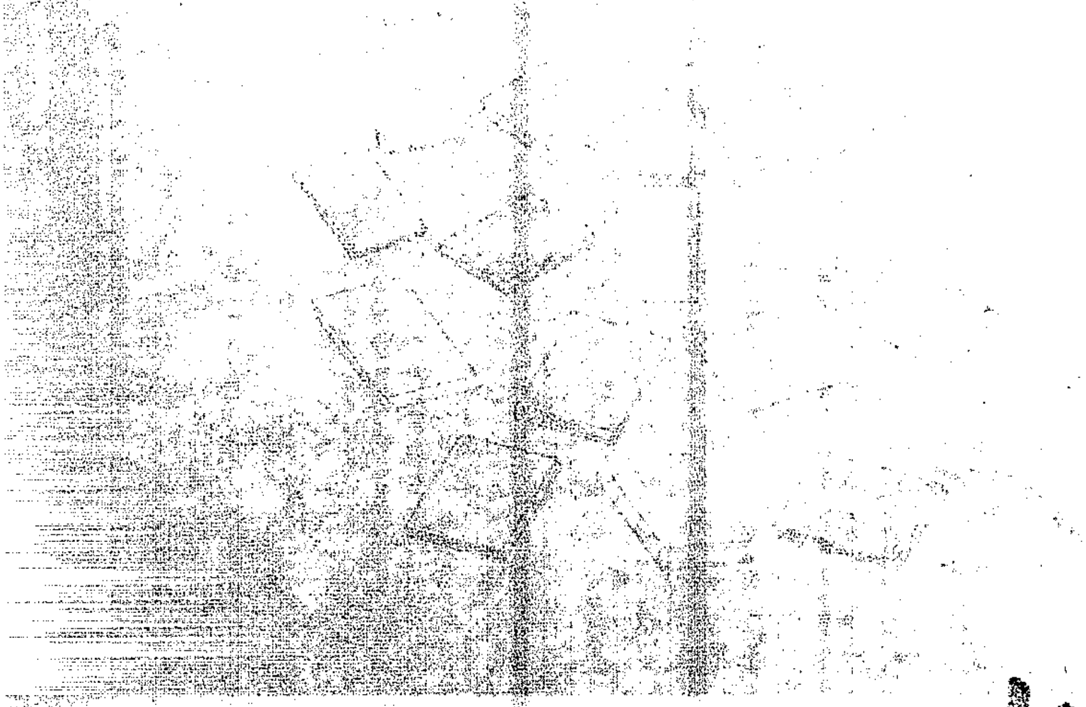
DIVISION OF HIGHWAYS

MATERIALS AND RESEARCH DEPARTMENT

RESEARCH REPORT

No. M & R 632812-1

Prepared in Cooperation with the U.S. Department of Commerce, Bureau of Public Roads January, 1967



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State of California
Department of Public Works
Division of Highways
Materials and Research Department

January 15, 1967

Lab Auth 632812
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Mr. J. C. Womack
State Highway Engineer
Division of Highways
Sacramento, California

Dear Sir:

Submitted for your consideration is:

LIME-SOIL STABILIZATION STUDY

a selected

LITERATURE REVIEW

Study made by .... Foundation Section
Under general direction of ...... Travis Smith
Work supervised by .... M. L. McCauley
Report prepared by .... Joseph Puleo

Very truly yours,

JOHN L. BEATON
Materials and Research Engineer

Attach

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Introduction and Purpose

The use of lime treatment to stabilize landslides, improve the strength characteristics of embankments, and to improve soft foundations may be possible in some instances. The purpose of this research project is to gain information and knowledge to be used in evaluating soils for potential lime stabilization treatment. This would require knowledge of many facets of lime-soil stabilization such as the migration of lime in a soil and the change of strength in a soil that can be affected by lime.

A quick literature search of limited scope was completed to provide background material. This initial search revealed much controversy relating to the lime-stabilization mechanism. As a result of the aforementioned literature search, a detailed review of the literature, with emphasis on problem identifications and "planning details" was proposed. Upon approval by the U.S. Bureau of Public Roads, this more extensive review of the literature was commenced.

The present study began with the collection of literature on lime stabilization topics that was available in our department. Other sources also provided pertinent literature.

In the early stages of the literature review it was discovered that a vast amount of useful information would be collected from the various papers. This raw material was immediately categorized under various topics (e.g., Ion exchange, Hydraulics, Zeta potential) for later review and assemblage. For our purposes, it was found that as one became more and more familiar with lime stabilization that the introduction and summary of a given paper was all that was necessary to determine what useful information could be gleaned. A very quick perusal of the body of the report noting tables, graphs, X-ray and D.T.A. tracings, pictures, etc., would then complete the initial review of the paper in question. Later as problems arose some papers were re-read.

The following procedure was used to catalogue the information. The pertinent parts of a given article were copied using a Xerox copier. These bits of information were then filed under an appropriate category. (Fifty categories were used originally but this number was reduced later to twenty-five).

The raw material was gathered from many different publications, ranging from the many reports of the Highway Research Board to construction magazine articles. The authors of these papers were from the U.S.A., Great Britain, Germany, Israel, Russia, India and Australia.

One objective of this report is to arrange the information in such a manner that it could be useful in subsequent lime stabilization studies. To achieve this goal the information was assembled in encyclopedic form and referenced. Many other bits of information not having a direct bearing on lime stabilization were included because of their proximate value to the subject. One such topic is entitled "Lime Stabilization vs Cement Stabilization."

The chief purpose of the appendix of this report is to direct the reader to the original paper.

Acknowledgments

The Foundation Section of the Materials and Research Department conducted this study. The work was done under the 1965-66 Work Program HPR-1(3) D-2-10 in cooperation with the U.S. Department of Commerce, Bureau of Public Roads.

Mr. K. K. Moore of the Texas Highway Department kindly provided seven reports authored by Mr. Chester McDowell, Supervising Soils Engineer for that department.

Mr. Dan M. Chamberlain, Sales Engineer for the Diamond Springs Lime Company, provided a most informative tour of his plant and discussion on the manufacture of lime.

Summary

Lime-soil stabilization can be an involved procedure.

What complication does exist can generally be attributed to the many different avenues that the lime can take on the way to stabilization. Variations in limes, soils, additives, and application techniques are some of the factors involved. Other widely diverse conditions can also influence the reactions.

The presence of organic matter can reduce the final strength of the stabilized soil, but certain additives to the system may solve this problem.

It appears that lime stabilization leads to permanent results. In the U.S.A. roads stabilized with lime are still in excellent condition after fourteen years of service. This can be attributed to a definite chemical reaction. The new cementing products which evolve (e.g., phosphates and pozzolanic hydrated silicates) are relatively insoluble.

The pozzolanic reaction is of singular importance because this is the reaction in which the clay particles themselves are directly involved. This reaction is normally a long-time strengthening process which can be accelerated in many cases by adding a small amount (0.5%) of common chemical additives, such as sodium hydroxide.

The permeability of a soil mass can be increased or decreased depending upon the percentage of lime added and the final compactive effort applied.

Despite the complicating factors lime stabilization can achieve highly desirable results at low costs.

RECOMMENDATION FOR FURTHER STUDY

The following is a proposed detailed work outline for continuing the Lime Stabilization study.

The information obtained in the literature search was used in preparing this proposal.

This phase of the study will be primarily oriented to those laboratory investigations concerned with the non-pozzolanic and pozzolanic reactions and their effect on the strength, Atterberg Limits, permeability, durability, etc., of various soils.

This is the Phase 2 listed in our original project proposal dated January 18, 1966. Phase 2 was originally designated "Laboratory Study" of the interaction of lime with various soils. However, Phase 2 will be divided into two parts with Phase 2a being completed prior to the beginning of Phase 2b.

Phase 3 of the original proposal designated "Field testing and evaluation study" will be dependent upon the results of Phase 2a and 2b.

Phase 2a

1. Gather approximately 30 soil samples from various areas of California where potential foundation problems exist.

2. All of the collected samples will be examined using X-ray diffraction, D.T.A., Grading, Sand Equivalent, Impact Compaction test, Atterberg Limits and R-Value test. A chemical analysis will also be run. The presence of such things as sulphates and silicates will receive special consideration because of their effect on lime stabilization.

   From the results of these analyses samples will be chosen that give a variety of soil classifications.

3. Six to ten samples will be chosen for use in Phase 2b.

Estimated Cost for Phase 2a

Field Work

Labor 10 days at $48/day	$ 480
Overhead 10 days at $24/day	240
Travel Expenses	200
Vehicle charges	200
	$1120

Laboratory Work

X-ray & D.T.A. 30 samples at $50	$1500
Chemical Analysis 30 samples at $100	3000
Grading 30 samples at $5	150
Atterberg Limits 30 samples at $20	600
Sand Equivalent 30 samples at $4	120
Impact Compaction 30 samples at $20	600
R-value 30 samples at $50	1500
	$7470

Say Total $8600

Of the total $8600, it is requested that $2500 be available in the fiscal year 1966-67 and that the remainder, $6100, be available in the 1967-68 fiscal year.

Phase 2b

Following Phase 2a the selected samples will be fabricated and then subjected to the tests shown in the following outline:

Lime	0%				1-3%				4-5%				6-8%			
Additive (NaOH)	0%		0.5%		0%		0.5%		0%		0.5%		0%		0.5%	
	E*	L**	E	L	E	L	E	L	E	L	E	L	E	L	E	L
Unconfined Compression Test	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Atterberg Limits					x	x		x	x	x		x				
Falling-Head Permeability		x						x			x	x				x
Durability																
a) Freeze-thaw***		x										x				
b) Erosion		x										x				
c) Reverse ion exchange****		x				x		x				x				
d) Water soak		x				x		x				x				
R-Value						x		x								
Identification																
a) X-ray diffraction						x		x		x		x		x		x
b) D.T.A.						x		x		x		x		x		x
c) Chemical analysis								x								

*E...early strength (7 day)
**L...Long-time strength (28 day)
***If freeze-thaw conditions exist at sample site
****Where brackish ground water exist at sample site

The unit sample testing outline would be followed for each of the 6 to 10 soil samples chosen in Phase 2a.

Estimate of Cost for Phase 2b

Ten unit samples at $1500/unit sample	$15,000
Preparation of report	2,500
Total	$17,500

1967-68	$ 9,000
1968-69	8,500
	$17,500

Preface

The comments catagorized in the appendix and mentioned in the synopsis do not necessarily represent our viewpoint. Rather than choose those statements which reflect only one point of view, a more objective approach was followed.

The many different viewpoints are represented within certain limitations. License was taken in selecting, where possible, those comments which were more clearly and unequivocally presented.

The various authors were not always directly quoted because the context may have been voluminous, reference made to various figures or other parts of the paper, or for numerous other reasons. In these instances it is hoped that the intent of the authors is preserved even though the wordage was altered.

Many of the comments listed under the various sections may appear to be in conflict with subsequent comments. While some may be true contradictions, others represent valid observations obtained under other conditions of soils, chemicals and environment.

The entire significance of the papers listed in the bibliography was by no means exhausted. But time was an important consideration in limiting the abstracting of the information.

SYNOPSIS OF THE APPENDIX

The physical properties of soils can be altered by the addition of chemical admixtures (27). They can be beneficial (e.g. NaOH, 27; $CaCl_2$, 61; and SC-100, 59) in some cases while detrimental (e.g. $Al(OH)_3$, 1; Na_2CO_3, 27; Na_2SiO_3, 27) in others. They can be flocculated, waterproofed, reduce surface tension, change the permeability, porosity, and Atterberg Limits. They can be used to pre-condition the soil for subsequent lime stabilization. Their presence in a soil can at first be beneficial but later on can hinder a desirable reaction (27, 56).

The addition of lime to soil results in many different actions. Adding lime to a soil increases the pH of the pore water (14). Providing there is enough lime present, an acid soil would be neutralized (1). Calcium ions will replace smaller, weaker H^+, K^+, and Na^+ of a soil through the action of base exchange (26). In the case of a sodium clay, NaOH is released which increases the pH. NaOH then acts as a catalyst to provide more available silicates in the form of sodium silicate. This silicate subsequently reacts with the lime to form sodium hydroxide and cementitious insoluble calcium silicates (19).

Many factors can either accelerate or hinder the aforementioned general mechanisms. Elevated temperatures (1, 24, 35, 58B etc.), high pH (35, 36, 45, etc.), common ion effect (1), catalyst (19), increased surface area, etc., can have a beneficial effect. While the presences of a waterproofer (1), an acid (Ca^{++} depletion), iron oxide (53), magnesium carbonate (20), etc., may hinder the production of the desired results.

On the other hand, although an acid (e.g. phosphoric) may deplete the Ca^{++} which would be otherwise available for the pozzolanic reaction, the calcium phosphate produced (64) behaves as a cement.

In general, the nonpozzolanic reactions consist of: carbonate production (which may be detrimental, 36), the aforementioned insoluble phosphates (19, 64), and the insoluble silicates (produced from sodium silicate and calcium salts, 64). The pozzolanic reaction consists of lime chemically reacting with the available silica and some alumina in the soil forming a cementing calcium silicate and aluminate (39) in various hydrated forms.

The pozzolanic reaction is singularly important because a great many soils have silica and alumina components. Soils which contain little or no pozzolans may be stabilized satisfactorily with lime when a pozzolanic material is added to the soil (24). Natural pozzolanic materials are not cementitious by themselves (24). The amount of cementation produced in a mixture of lime-soil is related to the reactivity and amount of the pozzolanic material (24). The primary source of strength in cement stabilized soils is the formation of cementitious compounds independently of the soil. Whereas in lime stabilization (except for carbonation, etc.) the lime (excess) acts directly with the active portions of the soil to form cementitious compounds (55).

One product of the pozzolanic reaction is tobermorite gel. Tobermorite gel coheres and adheres (66). This immediate reaction, formation of small amounts of tetracalcium aluminate hydrate, is supplemented by a somewhat slower reaction of the silica with lime to generate tobermorite gel (35).

Although quartz, mica, illite and even pyrophyllite are considered less reactive than clays, they may also react under appropriate conditions and give rise to similar cementitious products (tobermorite gel and a calcium aluminate hydrate). Reaction of lime with quartz generated tobermorite gel, even at 60°C (35).

The calcium silicate hydrate has been called "tobermorite gel" because of its similarity to the natural mineral tobermorite. This gel is the most important constituent of hardened portland cement (66).

The P.I. of the lime-soil mixtures has no relation to strength (2). In all probability, the degree of "stabilization" of a soil is most likely to be reflected by changes (increases) in the PL and to a lesser degree in the SL (44). Experience indicate that there is an immediate process responsible for the "amelioration" of the water-sensitive properties of untreated clay soil (35). Following flocculation there is a reduction in the thickness of the moisture film surrounding the clay grains. This is reflected in a reduction of the plasticity (26).

It appears that lime must chemically react with a soil to reasonably improve the strength (with the possible exception when quick lime is used only to reduce the moisture content of a soil). But the strengthening may not become significant until peripheral reactions are first satisfied. These peripheral reactions may be: acid neutralization (1), base exchange (3), and physical adsorption (not strictly chemical)(35), to mention a few.

These "ameliorating" effects (35) appear to be rapid and distinct from the long-time cementitious reaction. It is these cementitious reactions (principally pozzolanic) that appear to give rise to strength increases. The major source of increased strength stems from the lime-soil pozzolanic reaction (58). The pozzolanic reaction requires lime in excess of the lime retention point for sufficient cementation (35). On the other hand, the lime-pozzolanic reaction's main gain-in-strength with time is due to the precipitation and cementation of the $CaCO_3$ (from CO_2 in the water), and the complex silicious and aluminous gels of calcium (72).

Normally low densities are undesirable; but not in the case of soils that are lime stabilized (26). In most instances the maximum dry density is decreased (58B). These lower densities might be because of the resistance offered by the resulting flocculated soil structure to the compactive effort in the attempt to obtain closer packing (72). However, the variations in density do not correlate with the improvement in strength (1).

When using quick lime to stabilize a lean clay, large increases in strength were noted. While using hydrated lime less impressive strength gains were observed (41).

We must be prepared for the lime-stabilized soil acquiring hydrophobic properties (1, 5, 26, 43, 53, 60). Also the soak strengths of lime-soil mixtures are increased by using sodium compounds (additives) (24).

Lime's drying effect on soils is accomplished in at least two ways. First, when quick lime is added to a soil, the pore water is used to hydrate the lime. Secondly, lime treating a clay type soil releases the bonded water which results in a drying action (26).

Although few data are available, the permeability of compacted soil-lime mixtures has been reported to be much less than that of compacted soil alone (35). "Experience with a montmorillonic soil shows that the addition of $Ca(OH)_2$ increases the permeability of the soil to 7%, beyond which permeability begins to reduce" (70). Lime-soil stabilization results in a flocculated soil structure which, while remaining porous, results in a higher permeable mass (72). Clay particles that were permitted to harden at a high density will be much less porous than those that have hardened at a low density (44). Slurry solutions injected into the soil voids harden to varying degrees and impart cohesion. Since they partially fill the voids, the permeability is also reduced (51). The penetration of gravity water, and rapid evaporation, can be stopped by forming water-resistant barriers through lime treating bases or subbases (39).

The presence of organic matter adversely affects the strength producing pozzolanic reaction (58). It is possible that certain soil profiles containing a large percentage of organic matter cannot be strengthened by lime treatment (58). In an organic soil-lime system, both the soil silica and the organic matter are competing for calcium ions (14). Moreover, the addition of most alkali additives not only solubilizes the soil silicates, but also intensifies the organic activity (14). The low strength of an Illite-lime mixture can be attributed to the organic matter (7%) which "complexes" the lime and upon soaking swells and ruptures the cementitious bonds (14). The calcium ions are absorbed by the organic matter and thus the calcium ion concentration is reduced (79). The addition of potassium (and sodium) per manganate, being a strong oxidizing agent, probably oxidize the carbon in fly ash with the production of K_2CO_3 (or Na_2CO_3)and MnO_2. Strength may be also benefitted by the oxidizing agents cleaning the surfaces of fly ash and thereby making them more available for chemical reaction with lime (1). A solution of $K_2Cr_2O_7$ plus H_2SO_4 will oxidize organic matter. Depressing the pH by adding sulphates will render the organic matter relatively inactive, and the benefit of sodium ions present can thus be achieved (79).

The theory that lime migrates through the soil mass, performing desirable functions, is unproven. Whether it be a true migration or some other process, a highly beneficial phenomenon does occur (74).

High pressure lime injection was reported to be successful in distributing lime to depths up to twenty feet (4).

Finally, the question of permanency is often raised. Ion exchange and other sorptive mechanisms are reversible. The "home" water softener resin after being saturated with Ca^{++} and Mg^{++} is regenerated by reversing the process using a highly concentrated NaCl solution. However, the development of strength is accompanied by distinct structural changes in the clay minerals. It seems certain that the changes (pozzolanic) are relatively permanent (13).

APPENDIX

ATTERBERG LIMITS
PI, PL, LL, etc.

Opening Statements

44* Zolkov — In all probability, the degree of "stabilization" of a soil is most likely to be reflected by changes (increases) in the PL (and to a lesser degree in SL).

The over faithful use of the PI concept has tended to obscure the need for a more precise classification.

The Limits

PI

35 Diamond and Kinter — It should be kept in mind that the PI is a composite parameter that may not accurately reflect real changes in the systems. For example, equal increases in the LL and PL following a given treatment would be reflected as "no change" in the PI.

Low Values

24 Herrin and Mitchell — For soils with low or no plasticity, fly ash and other pozzolanic materials may be added to the soil with the lime to aid in the cementing action.

26 Gutschick — Low or nonplastic soils respond better to cement or asphalt than to lime.

39 Amer. Road Builders' Assoc. — PI values lower than 10 do not react as readily with lime. Soils with low PI's can often benefit by Lime treatment by adding a pozzolan, volcanic ash, expanded shale or sometimes a reactive clay.

Higher Values

24 Herrin and Mitchell — Lime cannot be successfully used with all types of soils, but is limited primarily to the stabilization of medium and highly plastic soils.

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*Numbers in this column refer to Bibliography

26 Gutschick	Soils with PI ranging from 10 to 50+ can generally be successfully stabilized with lime.
	LL
35 Diamond and Kinter	Calcium sautrated clays have lower LL than corresponding sodium or certain other cations.
44 Zolkov	It is evident that additions of NaCl and $CaCl_2$ affect the soil essentially in a very similar manner, except that the additions of NaCl lowers the LL more. Additions of lime to a fat clay caused LL to drop immediately after mixing, the smaller additions being of greater importance. Later on the LL rose considerably. Whether the LL of a cemented clay rises or falls is dependent on, among other factors, the arrangement and density of the soil particles at the time of the cementation.
55 Dumbleton	At earlier ages, the small percentage of lime added to a heavy clay (London Clay) frequently gave considerable increases in the LL, whereas, larger percentages of lime often gave smaller LL increases.
	PL
44 Zolkov	Adding $CaCl_2$ or NaCl to a fat clay (silty clay) gave no significant change in the PL of the final mix.
	PL vs LL
35 Diamond and Kinter	The LL is more sensitive to the kind of cation than is the PL.
	Plasticity
58B Thompson	The successful use of lime to alter soil plasticity and workability is not highly dependent on the chemical and mineralogical properties of the soil. However, such factors as type of clay mineral and the clay content may influence the quantity of lime required to achieve a satisfactory level of stabilization.
71 Kumbasar and Togrol	Increase in plastic and shrinkage limits may not always be accepted as an improvement in soil properties.

	Strength
2B McDowell	The PI of the soil-lime mixtures has no relation to strength. 4½% limed soils have more tendency for the PI to increase with age than 8% lime mixtures. Clay-lime systems might still be useful for subbase material if the PI does not increase with age.
35 Diamond and Kinter	For a number of lime-soil systems aging generally results in the changing of the PI from the earlier PI values.
	Soils
	Gravels, Disintegrated Granite and Caliche
24 Herrin and Mitchell	Only a small percentage of lime is needed to lower the PI of these materials.
	Loess
5 Brand and Schoenburg	The PI of a lime treated loess dropped to 2.0 from 4.8 before treatment. The LL rose from 22.8 to 24 while the PL rose from 18.0 to 22.0.
41 U.S. Dept. of Commerce	The Vicksburg loess (a lean clay) with a PI of 20 before lime treatment fell to 16 after the treatment.
	Clays
16A Hilt and Davidson	Large increases in the plastic limits of clayey soils can be obtained by adding small quantities of lime, $Ca(OH)_2$. The largest increases are in soils containing montmorillonite; illitic-chloritic clayey soils are affected somewhat less, and the plastic limits of kaolinitic clayey soils are the least changed
	Miscellaneous
20 Wang, Davidson and Rosauer	At the present time (1962) no conclusion can be drawn as to how lime quality would affect another soil property, such as plasticity.
26 Gutschick	Following flocculation there is a reduction in the thickness of the moisture film surrounding the clay grains. This is reflected in a reduction in plasticity, i.e., if the films are

thick, the clay particles are shielded so as not to come in intimate contact with their neighbors, thus, causing low stability and a highly plastic state.

33	Hoover	All sections pretreated with lime were allowed to react for a minimum of 48 to 72 hr before addition of stabilizing agent. As a means of checking the adequacy of this specification, sieve analysis, LL and PI were run on samples of lime-pretreated soil following 0 (untreated soil) 1, 6, 16, 24, 48 and 72 hr of curing.
35	Diamond and Kinter	Experience indicate that there is an immediate process responsible for the "amelioration" of the water-sensitive properties of untreated clay soil.
64	Woods, Berry and Goetz	If only a change in soil plasticity is desired any class of lime will do.
71	Kumbasar and Togrol	In some cases it was observed that as the difference between plastic and shrinkage limits increased, on the addition of lime, the possibility of development of cracks also increased.
79	Wissa and Halaby	The Atterberg limits were determined for all the soils in both the natural and air dry conditions. If there were any differences between the two conditions, the limits were also run on the soils in the oven dry condition.

CEMENTATION

In General

16A	Hilt and Davidson	Lime added above the lime fixation capacity level forms cementation products.
18	Mitchell and Hooper	Cementation is of minor importance in the overall soil-lime reaction.
55	Dumbleton	Portland cement hydrates to produce cementitious compounds independently of the soil.

Formation of Cementing Compounds

26 Gutschick

Following base exchange

1. The lime begins eating into clay particles (at high pH) releasing silica and alumina ions.

2. In the presence of moisture, hydration occurs forming:

   a. Calcium silicate hydrate (similar to tobermorite)
   b. Calcium silica aluminates (similar to hydrous garnets)
   c. and products from natural pozzolans.

73 Mateos

Samples of bentonite and 10% $Ca(OH)_2$ were compacted at optimum moisture content; they were then cured separately under vacuum, ordinary, and CO_2-saturated moist atmospheres for 7 days and 28 days. X-ray examinations followed after each curing period. Extensive carbonation of the $Ca(OH)_2$ was detected in the samples cured under CO_2-saturated atmosphere. Slight carbonation was found in the samples cured in the open air, whereas no carbonation was found in vacuum cured specimens.

EFFECTS OF CARBONATION ON SOIL-LIME STRENGTH

Curing Condition	Unconfined Compression Strength, in psi 7 day	28 day
Vacuum	240	370
Ordinary atmosphere	250	320
CO_2 saturated	100	220

This indicates that carbonation of $Ca(OH)_2$ yields low strength in the bentonite stabilization with lime and pozzolanic reaction products appear to be considerably stronger cementing agents than the $CaCO_3$.

Agents

1 Davidson, Mateos and Katti

The following materials form cementing compounds in the lime-fly ash reaction:

1. $Al(OH)_3$
2. $Fe(OH)_3$
3. $CaCO_3$

24 Herrin and Mitchell

Fly-ash or other pozzolanic materials aid the cementing action.

44 Zolkov

The products of the pozzolanic reaction are cementing agents.

64 Woods, Berry and Goetz

Lignosulfonates act primarily as a binder.

70 Sridhara — Complex cementitious compounds are formed when the following materials are added to soil-lime mixes:

1. NaOH
2. Sodium silicate
3. Na_2CO_3

Effect of Delay Compaction

2F McDowell — Laboratory and field studies indicate that the cementing action of lime with soil does not begin until the mixture is compacted into a dense mass.

18 Mitchell and Hooper — Delayed compaction reduces the effectiveness of possible cementation.

CHEMISTRY

Pre-Stabilization Conditioning

Flocculation

7 Boynton — The EMF (Zeta Potential) that holds the bound water film to the clay particle is reduced by the exchanged Ca^{++} replacing the smaller, weaker H^+, K^+ and Na^+.

26 Gutschick — Accompanying base exchange is a lowering of the zeta potential which causes a flocculation of the particles and a reduction in the thickness of the absorbed halo-like moisture films surrounding the clay grains.

35 Diamond and Kinter — The "ameliorative" affects is due to the limited chemical reaction at points of contact between edges and faces of primary clay particles within the "flocs" formed by the normal electrolyte effect of adding lime.

Various salts, alcohols, acids and ketones will also flocculate the soils.

79 Wissa and Halaby — To a 2:1 aqueous solution by weight of dry soil was added enough $CaCl_2$ to give a molarity of 0.01, and sufficient time was allowed for complete flocculation to take place.

Waterproofing

1	Davidson, Mateos and Katti	Some of the weak bases formed, such as $Al(OH)_3$ and $Fe(OH)_3$, give the soil waterproofing properties. $2AlCl_3 + 3Ca(OH)_2 \longrightarrow \underset{\text{Weak base}}{2Al(OH)_3} + 3CaCl_2$

Stabilization

Permanency

2E	McDowell	The history of ancient lime mortars and pozzolanic mixes, such as were used in construction of Roman roads, indicates that some lime mixtures have a high degree of permanence. Like many other mixtures the permanence of such mixtures depends upon good design and construction practices.
13	Eades and Grim	Because the development of strength is accompanied by distinct structural changes in the clay minerals, it seems certain that the changes are relatively permanent.
26	Gutschick	Based on the definite development of new cementing compounds accompanying the breakdown of the clay structure and the pozzolanic action, it appears that the stabilized material reflects permanent changes.
78	Urquhart and Babbitt	Calcium carbonate is insoluble in the absence of carbon dioxide.

Hinders

1	Davidson, Mateos and Katti	A chemical additive to the lime stabilization process may act as a catalyst, as an inhibitor or as a component of the pozzolanic reaction. The acid salts (eg $AlCl_3$) may impede the development of strength. $2AlCl_3 + 3Ca(OH)_2 \longrightarrow 2Al(OH)_3 + 3CaCl_2$ Thus, the $AlCl_3$ not only robs the lime at the expense of the pozzolanic reaction, but then acts as a waterproofing agent further slowing down the slow pozzolanic reaction.
55	Dumbleton	At present it appears that soils are unsuitable for stabilization with lime if they contain more than about 0.5-1.0 percent of sulphate ions.

56 Sherwood	It seems probable that the formation of ettringite is also responsible for the disintegration of lime (also cement) stabilized soils except that in these cases the ettringite is derived from a reaction between calcium sulphate and clay.

Cementation

Non Pozzolanic Reaction

Carbonation

1 Davidson, Mateos, and Katti	The precipitated calcium carbonate contributes cementation to the system.
7 Boynton	$Ca(OH)_2 + CO_2 \longrightarrow CaCO_3 + H_2O$
19 Mateos and Davidson	$Ca(OH)_2 + Na_2CO_3 \longrightarrow CaCO_3 + 2NaOH$ $Ca(OH)_2 + Li_2CO_3 \longrightarrow CaCO_3 + 2LiOH$
36 Davidson, Demirel and Handy	Curing of partially mixed soil and lime before final mixing improves pulverization, but this procedure has been found to be detrimental to the lime-soil reaction due to exposure to air containing CO_2.
54 Zube and Gates	Lime treated soils should not be permitted to dry out after mixing because carbonates are rapidly produced.
58 Thompson	Lime carbonation is not desirable since it reduces the amount of lime that can participate in the very important pozzolanic reaction. It forms relatively weak carbonate cementing agents.

Insoluble Phosphates

19 Mateos and Davidson	Sodium phosphate reacts with lime to form calcium phosphate, which may be cementitious.
64 Woods, Berry, and Goetz	Phosphoric acid reacts with calcium or other cations in a clayey soil to produce insoluble phosphates which behave as a cement.

Insoluble Silicate

Sodium silicate reacts with calcium salts to give an insoluble calcium silicate cement. This reaction has been utilized for a process of pressure injection of chemicals into troublesome foundation soils. As yet no use has been made in highways.

48A Eckel and Root

Most chemical injection processes use sodium silicate in combination with one or more other chemicals which yield silica-gel in the interstices of the soil. This is commonly applicable only to sand soils at least 0.1 mm grain size.

51 Peck, Hanson and Thornburn

Water-glas and $CaCl_2$ form a cohesive binder, but the efficiency of the procedure decreases rapidly as the grain size of the sand decreases. It also depends greatly upon the chemical composition of the groundwater.

Pozzolanic Reaction

78B Urquhart and Gilkey

Pozzolanic materials, finely divided siliceous and aluminous substances, not cementitious in themselves, combine with hydrated lime and water to form stable compounds of cementitious value.

79 Wissa and Halaby

The following equations represent what is known as a pozzolanic reaction:

$$Ca^{++} + 2(OH)^{-} + \underset{\text{(soil silica)}}{SiO_2} \longrightarrow CSH$$

$$Ca^{++} + 2(OH)^{-} + \underset{\text{(soil alumina)}}{Al_2O_3} \longrightarrow CAH$$

Products Formed (Lime-Soil Reaction)

11 Diamond

At or near room temperature

$$Ca(OH)_2 + Al\text{(bearing mineral)} \longrightarrow C\text{-}A\text{-}H$$

35 Diamond and Kinter

Variables - the kind of clay and the reaction conditions (especially temperature). Commonly, there are at least two phases:

1. A calcium silicate hydrate usually tobermorite gel
2. A calcium aluminate hydrate an impure tetra calcium aluminate hydrate (7.6Å basal spacing)

at temperatures only slightly above normal room temperature a different calcium aluminate hydrate phase is produced namely: the cubic tricalcium aluminate hexahydrate.

Quartz, mica, illite, and even pyrophyllite considered less reactive than clays may also react under appropriate conditions and give rise to similar cementitious products. Reaction of lime with quartz generated tobermorite gel, even at 60° C. Both tobermorite gel and the 7.6Å calcium aluminate hydrate product were formed by reaction of lime with mica, illite and pyrophyllite.

There is an immediate but limited chemical reaction at the points of contact between the edges and faces of primary clay particles within the flocs formed by the normal electrolyte effect of added lime. This reaction is visualized as the formation of small amounts of tetracalcium aluminate hydrate by the reaction of the exposed $Al(OH)_x$ groups at the edges of the clay surfaces with lime sorbed on the faces of adjacent surfaces. This immediate reaction is supplemented by a somewhat slower reaction of the silica with lime to generate tobermorite gel.

39 Amer. Road Builders' Assn.

Following base exchange, the chemical reaction of lime with soils produces a definite "cementing or hardening" action in which the lime reacts chemically with available silica and some alumina in the raw soil or with pozzolan additives, like fly ash, forming calcium silicate and aluminate.

Some Variables

Lime/Fly Ash Ratio

1 Davidson, Mateos, and Katti

Two lime/fly ash ratios were investigated:
1:9 and the 2:8
7 day strengths - similar
28 day strengths - difficult to conclude
4 month strengths - 2:8 ratio best

64 Woods, Berry and Goetz

Best Ratios 1:9 to 4:6.
For treated clays susceptible to freeze-thaw damage, 25% to 30% lime to fly ash is best. For sandy soils best ratio is 1:5. Combined (Silt to Clay) 10% to 30% is a good ratio for cementation bonding.

pH

35 Diamond and Kinter

Evidence exists that at high pH silica is more soluble, resulting in the pozzolanic reaction speed-up.

36 Davidson, Demirel and Handy	A minimum pH of approximately 10.5 was necessary for a pozzolanic reaction.
79 Wissa and Halaby	When lime is added to a soil there results an immediate increase in the pH due to the partial dissociation of the calcium hydroxide. The hydrous silicas and aluminas then act as buffers and react rapidly with the cations and a lowering of the pH occurs.
	Accelerators
	Chemical
1 Davidson, Mateos, and Katti	Existing evidence shows that the pozzolanic reaction is slow under normal curing conditions. Many chemicals can be added to this reaction to accelerate it. Alkaline additives increase the amount of available hydroxyl ions and as a result the pozzolanic reaction may be accelerated by the increased solubility of the siliceous material. e.g. $NaOH + Silicates \longrightarrow Na - Silicates$ $Na-Silicates + Ca(OH)_2 \longrightarrow Ca-Silicates + NaOH$.
14 Ladd, Moh, and Lambe	Sodium compounds, $NaOH$, Na_2SO_4, Na_2CO_3 and $NaAlO_2$, either provide additional silica (that is sodium metasilicate - $Na_2SiO_3 \cdot 9H_2O$) or make the soil silica more reactive and at the same time control the rate of reaction between lime and silica to facilitate a more uniform distribution of the cementitious calcium silicates.
	Temperature
58B Thompson	The pozzolanic reaction rate is relatively slow at normal temperatures (75°F) but at high temperatures the reaction proceeds at a much faster rate.
	Retarders
1 Davidson, Mateos, and Katti	Lime is subject to conversion to calcium carbonate during long curing periods; when this takes place pozzolanic action ceases.
64 Woods, Berry, and Goetz	Depletion of the Ca^{++} hinders the pozzolanic reaction. The calcium ions exchange with sodium ions in Na-Montmorillonites.

Miscellaneous

Aluminate

11 Diamond

Calcium aluminate hydrates have recently been reported to form as products of reaction between aluminum-bearing clay minerals and $Ca(OH)_2$ at or near room temperature.

Aging

18 Mitchell and Hooper

It is concluded that the observed chemical changes on aging serve mainly to increase flocculation and reduce water affinity of the soil.

56 Sherwood

A London clay containing 2% (as SO_3) of calcium sulfate was stabilized with lime. X-ray diffraction and DTA revealed that the calcium sulfate had disappeared from the specimens that had been immersed in water. As there was insufficient water present for the calcium sulfate to have been completely leached from the specimen sampled, this can only mean that it had reacted with the clay. There was also some evidence that attringite (calcium sulpho-aluminate) had been formed as a result of this reaction.

Amelioration

35 Diamond and Kinter

Experience indicates that there are at least two distinct stages of reaction involved:

a. the immediate or rapid processes responsible for the "amelioration" of the water-sensitive properties of untreated clay soil.

b. The slower, long-term reactions resulting in formation of the final cementitious products that are indicated by the gradual development of strength in compacted soil-lime mixtures.

Heat of Reaction

24 Herrin and Mitchell

$$CaO + CO_2 \longrightarrow CaCO_3 + 21\ KCal$$
$$CaO + H_2O \longrightarrow Ca(OH)_2 + 15.3\ KCal$$

Ionization Constant

1 Davidson, Mateos and Katti

Since lime has a lower ionization constant than $CaCl_2$, the concentration of Ca^{++} from lime is lower than that from $CaCl_2$.

73 Mateos

$Ca(OH)_2$ dissociates in the soil because no traces of it are found in the X-ray analysis.

79 Wissa and Halaby

When lime is added to a soil there results an immediate increase in the pH due to the partial dissociation of the calcium hydroxide.

Mechanism

15 Taylor and Arman

A study of the soil-lime reaction was made, based on information yielded by the soil characteristics tests. These tests revealed that lime has an initial reaction, taking place during the first 48 to 72 hr after mixing, and a secondary reaction, which starts after this period and continues indefinitely.

Particle's Surface Charge

61 Kleinfelder

By the nature of their chemical composition, a clay particle has negative surface charges and positive interior charges, even though their net charge may be zero. The effect of surface charges on a heavy particle (such as sand) is insignificant. The effect on very small particles of low mass is considerable however, and these surfaces forces can greatly alter the clay's behavior.

Reaction Rates vs Surface Area

10 Greenberg

Four different colloidal silicas were chemically attacked by $Ca(OH)_2$. The reactions rates are different but are not necessarily proportional to the surface areas of the silicas. (It should be noted that the absolute rate of reaction is slower for these large crystallite size, chemically-pure, calcium hydroxides than for fine-particle size, commercial grade limes.)

Volume Factor

56 Sherwood

Disintegration of lime stabilized soils, which have sulfate ion present, can probably be traced to the formation of ettringite from a reaction between calcium sulfate and the clay. Ettringite occupies a greater volume than the reactants resulting in an expansion which is destructive.

COHESION

Cohesiometer Values

24 Herrin and Mitchell — These values increased as the lime content increased up to about 5%. Above this 5% level the cohesiometer values decreased.

Lime Fineness Effect

2B McDowell — Fine limes are more effective in decreasing cohesion than coarse limes.

Slurry Injection

51 Peck, Hanson and Thornburn — Slurry injectioned into sands and silts partly fill the voids and impart cohesion, although there is a reduction in permeability.

The Temperature Factor

55 Dumbleton — At low temperatures, cohesive soils stabilized with lime and with cement showed similar increases of strength with increase of temperature. But at higher temperatures the soil-lime showed relatively greater increases in strength than the soil-cement. These tests consisted of 10 cohesive soils stabilized with 10% lime.

CURING

Types

39 Amer. Rd. Builders Assoc. —

1. Moist cure
2. Membrane curing; seal the surface with a coating (e.g., bituminous materials).

Time Factor

2E McDowell — An expansive clay basement soil was ponded for 30 days after which it was treated with waste lime (approx. 4%) and cured for three days. At the end of three days, heavy loads of crushed stone were easily hauled over the compacted mass.

17 Anday — Accelerated laboratory curing can predict the unconfined compressive strength for field cured specimens at summer temperatures. The strength will be a function of their maturities.

18 Mitchell and Hooper — The observed chemical changes on aging serve mainly to increase the flocculation and reduce the water affinity of the soil. Increasing the curing time (35 to 60 days) tends to slightly decrease the strength and increase the swell.

23	Dawson and McDowell	The specimens were carefully lined up so that the maximum stress would be at the line of the original break. By some process of autogenetic healing, the specimens developed a considerable strength in the period of re-curing.
53	Zube, Gates and Hatano	Mitchell and Hooper indicated that for a given compactive effort, a mixing and compaction delay above 24 hours is not desirable.
55	Dumbleton	The effects of delay between mixing and compaction are not so severe with soil-lime mixtures compared with soil-cement systems.

DENSITY

Low

24	Herrin and Mitchell	Lime treatment resulted in the lowering of the maximum dry density of fine-grained soils, natural gravels, and gravel binder mixes.
26	Gutschick	Normally low densities are undesirable but not in the case of soils that are lime stabilized. The optimum moisture content is increased. The change may be 5% or more.
58B	Thompson	In most instances the maximum dry density is decreased and the optimum moisture content is increased. A 2-5 pcf density decrease is typical while a 1-5% optimum moisture increase is typical.
72	Nagáraj	Lower dry densities might be because of the resistance offered by the resulting flocculated soil structure to the compactive effort in the attempt to obtain closer packing.
73	Mateos	Lime treatment lowers the maximum density of the common soils and was generally accompanied by an increase in optimum moisture content.

High

24	Herrin and Mitchell	High densities tend to improve durability. Strengths of these lime-soil-fly ash mixes were increased during the wetting-drying tests.

Miscellaneous

1	Davidson, Mateos, and Katti	The variations in density do not correlate with the improvements in strength.

55 Dumbleton — Although with fresh mixtures lower densities were obtained with lime than with cement, the lime and cement mixtures gave equal densities after a 3½-hour delay. This property of soil-lime mixtures gives greater flexibility in construction operations. If inadequate densities are obtained the material may be reworked and the moisture content adjusted. If heavy rain occurs during the work, the material may be dried out to the required moisture content.

DURABILITY

Opening Statement

2E McDowell — Many jobs in south central states up to 14 years old (at 1959 writing) are still in excellent condition. A few jobs in New Mexico and California have withstood severe climatic conditions for several years without damage from freezing and thawing: Final conclusions with respect to this matter will depend upon future experience.

44 Zolkov — In fact, with time some of the stabilized soils become less stable than the untreated natural soils (Winterkorn in relation to cohesive soil stabilization and the effect of soil microbes).

Tests

24 Herrin and Mitchell — Strengths were increased during the wetting-drying test. A soniscope is used to measure durability.

32 Laguros — The freeze-thaw test indicates that the use of NaOH, Na_4SiO_4 or $CaCl_2$ in lime-soil mixtures greatly increases weather resistance.

53 Zube, Gates and Hatano — The durability of a lime-soil mixture can be indicated by using a sand bath test.

In General

24 Herrin and Mitchell — High density tends to improve the durability of soil-lime-fly ash mixtures.

When the soils were stabilized with lime in the laboratory they had very little resistance to the freeze-thaw test; however, the soils seemed more durable when subjected to actual field durability tests.

56 Sherwood — The presence of the sulphate ions on soils treated with lime can lead to disintegration of the soil mass.

64	Woods, Berry and Goetz	Lime treated clays are often susceptible to damage from the freeze-thaw cycle.

FLOCCULATION

Importance

35	Diamond and Kinter	Since many soils in need of stabilization are naturally calcium saturated, flocculated, or both, the first two mechanisms (cation exchange, flocculation) can no longer be seriously considered. The achievement of flocculation is clearly not the mechanism by which lime stabilizes soils. Many chemical agents (e.g., various salts, alcohols, acids and ketones) induce immediate flocculation when mixed with clays.

Cause

26	Gutschick	Accompanying base exchange is the lowering of the zeta potential, which causes a flocculation of the particles and reduction in the thickness of the adsorbed halo-like moisture films surrounding the clay grains.

Physical Changes

18	Mitchell and Hooper	Flocculation increases with time.
26	Gutschick	Flocculation of clay particles, forms silt and even larger sizes. This is shown up by a substantial decrease in the soil binder content (-40 mesh).
58B	Thompson	Flocculation results in an apparent change in soil texture, the clay particles "clumping" together into larger sized "aggregates."
61	Kleinfelder	The properties of a clay depend heavily on whether they are flocculated or dispersed.
72	Nagaraj	The decrease in dry density might be because of the resistance offered by resulting flocculent soil structure to external compactive effort in the attempt to obtain closer packing.

Strength

1	Dumbleton	Base exchange and flocculation produce an immediate increase in strength.

Permanency

26	Gutschick	Some engineers have questioned the permanency of lime stabilization feeling that if it only involved flocculation and base exchange, the reaction could be reversed and the stabilization benefits nullified. However, based on the definite development of new cementing compounds accompanying the breakdown of the clay structure and the pozzolanic action, it seems certain that the changes are relatively permanent.

HYDRAULICS

Water Stability

24	Herrin and Mitchell	Soak strengths of lime-soil mixtures are increased by using sodium compounds.
44	Zolkov	The PI of a fat clay soil is not a good indicator of its water stability.

Water Resistance Barrier

1	Davidson, Mateos, and Katti	Various soils can be waterproofed by treating the soil with $Al(OH)_3$ of $Fe(OH)_3$.
5	Brand and Schoenburg	The loess acquired hydrophobic properties after it was lime treated.
26	Gutschick	Lime stabilization increases the resistance of the soil mass to water absorption and capillarity.
43	Puzinauskas and Kallas	Certain chemicals added to various soils impart waterproofing qualities. Ortho-phosphoric acid, $Ca(OH)_2$ and portland cement are useful for this purpose.
53	Zube, Gates and Hatano	The lime also serves as a moisture barrier.
55	Dumbleton	There is less resistance to the action of moisture with lime treatment than with cement treatment. Therefore, after lime treating a road the surface should be sealed to minimize the ingress of surface water.
60	Riha	To create a moisture barrier use lime.

Moisture Content

26	Gutschick	Lime treating a clay type soil releases the bonded water which results in a drying action.
		An expansive soil was pre-expanded by ponding for 30 days. It was then drained and 5% lime was added. The resulting soil was firm following compaction.
41	U.S.Dept. of Commerce	The bearing capacity of a weak subgrade can be improved by adding quick lime to the overlying soil layer. This is due to water being extracted from the subgrade for the hydration of the lime.
44	Zolkov	By rewetting the soil well in advance of a research study the influences of changes in the soil due only to rewetting can be minimized and better control can be achieved. The portion of the moisture content at LL that is due to water in the voids of the individual aggregates, varies, and so accordingly should the LL.
65	Corps of Engineers	The percentage of loss of water in a soil is approximately equal to one-half of the percentage weight of the added quick lime.
71	Kumbasar and Togrol	In certain clays, the addition of lime yields a less strongly flocculated structure that results in a decrease in the optimum water content and an increase in the maximum dry density for the same compactive effort.

Rain

24	Herrin and Mitchell	Subgrades that are treated with lime are less affected by rain than untreated subgrades. During construction, lime treated bases seem to be little affected by rain.
63	Russam and Dumbleton	The unusual sensitivity to rainfall of a soil, at the Melbourne Airport, was found to be due to the high concentration of NaCl in the soil, together with 40% of the clay mineral montmorillonite. During the rain the NaCl content was reduced. The montmorillonite then tended to disperse which resulted in a rapid decrease in strength. The addition of 4% lime to the soil hindered dispersion and thereby gave a stronger and more stable material.

Permeability

3	McDowell and Moore	Permeability and capillarity are two different things. Laboratory personnel often observe a fast rate of wetting in moist-cured, partially dried specimens. This should not be mistaken as an indication of a high rate of permeability. Compacted lime-soil mixtures are particularly effective for repelling water percolation.
32	Laguros	The chemicals ($NaOH$, Na_4SiO_4, and $CaCl_2$) are effective in promoting the compressibility properties of the lime-montmorillonite clay by increasing its permeability.
35	Diamond and Kinter	Though the data is limited, the permeability of a compacted lime-soil mixture is reported to be much less than compacted soil alone.
39	Amer. Rd. Builders' Assoc.	The penetration of gravity water, and rapid evaporation, can be stopped by forming water-resistant barriers through lime treating bases or subbases.
51	Peck, Hanson and Thornburn	Caution! If the coefficient of permeability of a soil lies between 10×10^{-4} and 10×10^{-6} cm/sec it will not be satisfactory for lime injection.
52B	Engin. News-Record	The permeability of fine sand lenses (alluvium) were reduced from 10×10^{-4} to 10×10^{-6} cm/sec by treating the sand with a mixture of bentonite and chemicals (primarily silicates). For all practical purposes the final product was totally impervious.
64	Woods, Berry and Goetz	During dry periods, dispersed clays can lower the permeability of a soil, which in turn reduces the rate of evaporation. But during the rain the dispersed clay swells and plugs the pores reducing further water penetration.
70	Sridhara	"Experience with black cotton soil (montmorillonitic) shows that the addition of $Ca(OH)_2$ increases the permeability of the soil to 7%, beyond which the permeability begins to reduce."
72	Nagaraj	Lime-soil stabilization results in a flocculated soil structure which, while remaining porous, results in a higher permeable mass that is stable to the action of water.

79	Wissa and Halaby	The $CaO + MgSO_4$, apart from having an increase in strength due to the drop in water content also shows a relatively steep increase of strength with time. One reason for this is that as the soil becomes more dense upon the introduction of the $MgSO_4$ there is a decrease in permeability. This could also partially explain the increased resistance to soaking.
		Testing
29	Tumay, Larew, and Meem	Rational permeability values of coarse and fine-grained soils can be obtained by using radioisotopes as the tracer. Water movement in a slide area can be traced using household bluing or fluorescein. But it must be used in neutral water.
		Marshy Soil Stabilized
24	Herrin and Mitchell	A marshy soil containing a large amount of organic matter and salt was successfully stabilized with lime. The underlying soft material did not break through when the treated subbase was rolled. Cement and asphalt stabflization was found to be unsatisfactory.
		Miscellaneous
25	Miller and Couturier	The water absorption test shows promise for evaluating lime-fly ash-aggregate compositions. This test showed the same trends as the strength and durability tests. The simplicity of this test would make it desirable.
44	Zolkov	Clay particles that were permitted to harden at a high density will be much less porous than those that have hardened at a low density.
47	Cleaves	A reasonably stable soil mass may become unstable when the cations are exchanged by the action of percolating waters.
51	Peck, Hanson and Thornburn	Slurry solutions injected into soil voids harden to varying degrees and impart cohesion. Since they partially fill the voids the permeability is also reduced.
58B	Thompson	Poorly drained soils (B horizon soils) are generally quite reactive to lime as compared with well drained soils.

79 Wissa and Halaby

The higher treatment levels (12% compared to 8%) were needed because of the less uniform mixing which occurs when stabilizers are added to wet soils. With the wet soils 50% to 100% higher levels were required. Improvements in the efficiency of mixing would probably reduce the required amounts of stabilizers. However, with the existing field equipment it is doubtful that successful stabilization of the wet soils can be achieved with a reasonable level of treatment.

ION EXCHANGE

Importance

35 Diamond and Kinter

Cation exchange can no longer be seriously considered as an adequate explanation for the stabilizing effects of lime on soil.

45 McBain

Puri and Uppal have emphasized that the BEC* of clay has a definite meaning only if the titration refers to a definite pH well on the alkaline side and they recommend use of the actual titration curves. In summary it should be pointed out that ion exchange is not the only way in which ions are sorbed. They may be sorbed by oppositely charged ions already on the surface, whether there by previous sorption or as ions which are part of the crystal lattice of the solid itself.

Soil Property Changes

The properties of a clay are profoundly modified by base exchange, which involves chiefly minor constituents whose determination in the present (1950) state of the commercial art is difficult and not precise.

A reasonably stable soil may become unstable or sensitive if perfolating water affects the exchangeable cations of the constituent clay mineral or leaches out soluble salts.

3 McDowell and Moore

The first chemical reaction which takes place is of a base exchange nature which lowers the PI and gives the soil a loose friable appearance.

*Base Exchange Capacity

7	Boynton	During the first stage, the clay mellows, through base exchange, so that pulverization can be readily achieved during the second mixing.
78A	Urquhart and Babbitt	When the base-exchange material is exhausted (Ca^{++} saturated) it is regenerated by allowing a solution of NaCl to stand in contact with it.
		Time Factor
26	Gutschick	Base exchange is an immediate reaction. Larger Ca^{++} replace the smaller, weaker, H^{+}, K^{+}, and Na^{+} of the clay.
45	McBain	Base exchange is slow requiring several days for substantial completion.
54	Zube and Gates	This action (base exchange) is rapid (within an hour or two) if the soil is pulverized and thoroughly mixed.
58B	Thompson	The cation exchange reactions do not occur within a short period of time if it is not possible to obtain an intimate mixture.
72	Nagaraj	The magnitude of alteration of surface characteristics and the time required for reaction are dependent on the type and quantity of clay mineral in the soil. 1. quick occurrence - kaolinite the exchangeable cations are held around the edges of the flakes and elongates the units. 2. slow occurrence - montmorillonite the exchange is predominantly on the basal plane surfaces.
		Results
30	Laguros, Handy, and Reign	The effect of lime on calcium montmorillonite shows a drastic change, yet there is no logical ion exchange reaction.
54	Zube and Gates	Fine plastic clay particles are agglomerated by base exchange into coarse friable particles.
55	Dumbleton	Base exchange and flocculation produce an immediate increase in strength.

Miscellaneous

35 Diamond and Kinter — The results of our recent experimental work contradict these hypotheses (lime fixation point, pH - dependent exchange sites). It is shown that cation crowding effect is, in reality, one of physical adsorption of $Ca(OH)_2$ onto the clay surfaces. We postulate that the ameliorative effects are due to almost immediate but limited chemical reaction at the points of contact between the edges and faces of primary clay particles within the flocs formed by the normal electrolyte effect of added lime.

45 McBain — A lagoon on Treasure Island in San Francisco Bay contained a clay which allowed water to escape through it. The problem was solved by converting the clay, through base exchange, into a sodium clay which has a very low permeability to water.

49 McNeal — The exchangeable cation has considerable effect on glycol retention by layer silicate minerals. The relative retention levels on homo-ionic clays are in the order of K less than Na less than Al less than Ca.

LIME

General Properties

Fineness

2B McDowell — May be it's somewhat like the coffee bean which may be pure but you need to grind it to make good coffee.

7. Boynton — In general, the purer and more concentrated the lime, the more finely divided it is.

1. -200 mesh hydrate. Contains real active lime.
2. +200 mesh hydrate. Contains much inert material.

Therefore, we recommend no more than 20% +200 mesh grading.

Availability

Almost always the finer the lime, the more available it will be.

		Carbonation
31	Walker and Karabulut	There are many cases in the field where lime is used which contains significant quantities of $CaCO_3$.
2F	McDowell	Lime should not be exposed to open air for more than 6 hours before being mixed with the soil.
59	Street and Highway Manual	The Texas Highway Department maintained stockpiles in the open of lime treated base material at strategic locations for small maintenance and repair jobs. Only the outside "inch" surface loses its effectiveness due to carbonation and overall this is insignificant.
		Waste Limes
7	Boynton	In general, the best of the waste limes lack uniformity.
		Pozzolanic Sensitivity
64	Woods, Berry, and Goetz	Pozzolanic reactions are extremely sensitive to the chemical class of lime; and the type desired must be specified in some detail. An exception is where only a change in soil plasticity is desired.
		Optimum Moisture Content
20	Wang, Davidson, and Rosauer	The final soil-lime mixture can differ as much as 2% when various commercial limes are used.
		Lime Specifications
2B	McDowell	It is believed that we should require our limes to be at least: 1. 90% hydrated lime 2. a minimum of 85% (-200 mesh) when wet washed Pay for lime on the basis of the purest grade.
7	Boynton	There is obviously a vast difference between limes of 90-95% available CaO and those of 70-80%, just as there is with similar concentrations of 100 proof whiskey vs 86 proof, and many other things.

Accordingly, we recommend a minimum of 90% available lime or a maximum of 95% total oxides (non-volatile basis) as a reasonable lime specification. This is the minimum quality of commercial lime generally produced.

It isn't this simple -

"Just add 12% more of the 80% product to meet the equivalent total free lime of the 90% product." Because of the higher percentage of +20 mesh material in the 80% lime that is largely nonreactive, about 25-35% more lime would be required for equivalence.

54 Zube and Gates — Early specifications for lime in California called for 85% $Ca(OH)_2$, requiring a high grade limestone to produce this product. Later, after an economic study in 1962, a 75% $Ca(OH)_2$ requirement was established (but requires a little more lime).

56 Sherwood — 92% $Ca(OH)_2$ was used

Miscellaneous

20 Wang, Davidson, and Rosauer — When evaluating a dolomitic lime, for use in soil stabilization, the present most reliable method considers:

1. the crystal size of the MgO
2. the amount of SiO_2 and R_2O_3 in the lime

	CaO	$Ca(OH)_2$
MW	56.08	74.10
Ca	71.5%	54.1%
O	28.5%	43.2%
H		2.7%
CaO	100%	75.7%
H_2O		24.3%
		Orthorhombic or Trigonal

LIME APPLICATION TECHNIQUES

"Drill-Lime" Stabilization

54 Zube and Gates — A new maintenance technique developed by Oklahoma Highway Department. Use for:

1. Correcting flexible pavement distress.
2. " sliding highway fills.

General Procedure

1. Drill holes through pavement - 9" dia., 30" deep and 5' centers.
2. Introduce hydrated lime into holes.
3. Add water.
4. Back fill, tamp and patch surface.

74 Roth

Post Stabilization Procedure

1. Drill holes - 12" dia., 2' deep, about 5' centers.
2. Place 25 lbs. of lime in hole.
3. Add enough water to form a thick slurry after stirring.
4. Backfill hole with borings and compact with pneumatic tamper.

High Pressure Lime Injection

4 Higgins

Using an adaptation of oilfield cementing equipment, lime slurry (up to 1.5% lime by weight) was injected by pressure (about 600 psi) to various depths in a hydraulically placed fill. The strength of the slurry was changed when the amount of the injection was changed to maintain the amount of lime being injected.

1. The injection apparatus was equipped with a mechanical seal at ground level for stopping feed-back around the injector.
2. During the injection process, a definite bulging or rising of the soil near the injection was noticeable.
3. Surface piping losses were somewhat reduced by driving wooden pegs into the soil at the point of escape.

Ground Water Lime Distribution

6 Williams, and Handy

The treatment (for stabilizing an active land-slide) consisted of augering holes through the fill on a 5-foot grid pattern, and seeding the saturated shear zone soil with quick-lime plus water for hydration. Hopefully the lime would slowly dissolve in the ground water and diffuse throughout the soil in the shear zone, changing its plasticity and internal friction. Treatment of the two lots required 20 tons of lime.

Ponding

2C McDowell

A building site foundation in Texas consisted of a clay formation encountered near the surface and extended for a depth of 50 feet or more. This expansive clay, Del Rio formation, has a PI of 40 to 70 and varies considerably in moisture content. Triaxial tests on undisturbed cores indicated a bearing capacity of at least 3 tons/sq. ft. using a safety factor of 2. Six feet of the clay was excavated and the basement soil was ponded for thirty days. Waste lime (4%) was then added to a depth of 12" and the mixture allowed to cure for 3 days. Following compaction, heavy loads of crushed stone were easily hauled over the compacted mass.

26 Gutschick

A ponding-stabilization foundation job built in Texas over a year ago (before 1960) demonstrated the pronounced drying action which occurs by lime releasing the bond water in the clay. On this job an expansive clay soil was pre-expanded by ponding for 30 days. After draining, 5% lime was added to the over-saturated soil; and within 4 hours after mixing started, the soil was firm enough to support a light pickup truck.

"Double-Application Method"

15 Taylor and Arman

This method proved itself capable of solving some of the more important problems in stabilization.

General Procedure

1. 1st application of lime (mix with the soil).
2. mellowing (rotting) period follows (keep moist).
3. 2nd application of lime (approx. 30 days after 1st).
4. compaction may immediately follow.

52A Engineering News-Record

Crews first scarified the top 6" of the compacted fill, then spread about 15 lb. of lime per square yard (3%) from pneumatic bulk haulers, generally in one pass. They watered heavily the area to be stabilized, then began preliminary mixing with a disc harrow and high-speed rotary mixers. Generally two passes of the mixers were enough. The layer was sealed with a 25-ton pneumatic roller, then allowed to cure for 48 to 72 hours. The lime and soil was then remixed with a scarifier and rotary mixers, adding more water in the process. It was then compacted with a 50-ton pneumatic roller, the surface bladed to grade and kept moist until the cement-treated base was placed upon it.

Miscellaneous

Allowable Delay (before compaction)

18 Mitchell and Hooper	1. The American Road Builders Assoc. points out that the mixed material may cure or age for 24 to 48 hours prior to compaction as long as optimum moisture conditions are maintained.
	2. McDowell states that soil-lime mixtures may be compacted any time within 2 days after mixing with delays up to 4 days permissible if heavy plastic clays are used.
	3. Delay between mixing and compaction is not detrimental provided extra compactive effort is used.

Fly Ash

39 American Rd. Builders Assoc.	Fly ash should be spread on the road before the lime is added. However, fly-ash and reactive clay soils have been successfully premixed at central mixing plants.

Lime Exposure

2F McDowell	Lime should not be exposed to open air on the job for more than six hours (before mixing).
54 Zube and Gates	Additional lime should be added, above laboratory indications, for construction purposes. Usually about 0.5%.

Lime Storage

59 Street and Highway Manual	The Texas Highway Dept. maintained stockpiles in the open of lime treated base material at strategic locations for small maintenance and repair jobs. The small amount of lime that loses its effectiveness through carbonation due to exposure is insignificant since it occurs in the outside "inch" surface of the stockpile.

Slurry Form

2D McDowell	When lime is used with granular materials the lime should be in slurry form.

2F McDowell

For pumping purposes, the maximum percent lime in the slurry should be not more than 40%.

Dry Form

7 Boynton

Because of limes pronounced drying action, a copious amount of water is required when used in the dry form. Use at least 5% over optimum.

Pulverization

It is generally impossible to effect adequate pulverization (all passing the 1" sieve and 60% passing the #4 sieve) by merely one mixing operation (regardless of the number of mixing passes). It necessitates a two stage mixing with a 1 to 2 day curing period.

34 Thomas, Jones, and Davis

Construction of a lime-soil subbase was relatively trouble-free. By its quick reaction with the clay, lime aided in pulverization and density was obtained after only a few passes of a pneumatic roller.

36 Davidson, Demirel, and Handy

Soils which are difficult to pulverize may be stabilized with lime treatment, but at the same time the pulverization requirements should be relaxed.

39 Amer. Road Builders Assoc.

If the clay is lumpy, a curing delay (moist cure for 24-48 hours) helps to "rot" the lumps which facilitates pulverizing.

65 Corps of Engineers

For cohesive soils it is possible to achieve a satisfactory job without thorough initial pulverization.

Powdered vs Liquid Trace Chemical "Accelerators"

1 Davidson, Mateos, and Katti

Most of the "accelerators" gave better results when mixed as a powder. The most noteworthy is Na_2CO_3 which gave a higher comparable strength:

7 day	28 day	4 month
71%	28%	18% above liquids

$CaCO_3$ is thought to be more effective when the carbonate crystals are formed on the grains. This is more apt to occur when the Na_2CO_3 is added in powdered form since when added in the mix water the $CaCO_3$ may be prematurely precipitated before compaction is completed. Another advantage is the slower production of NaOH (using powdered Na_2CO_3) may be more favorable to sustain formation of pozzolanic products.

Caution

2F McDowell

Bases should not be reworked after 7 days from compaction unless a small (1%) amount of lime is added.

Mixing Difficulty

79 Wissa and Halaby

The main difficulty involved with wet soils is in obtaining adequate mixing in of the stabilizer.

LIME RETENTION

16A Hilt and Davidson

Lime fixation in clay does take place.

Lime fixation capacity of montmorillonite or kaolinite soil is the same as the optimum lime additive for maximum increase in PL of the soil. Lime added above the lime fixation capacity caused the formation of cementing material with clayey soils.

35 Diamond and Kinter

In contradistinction, we suggest that with many soils, small increments of lime less than the lime retention point do in fact add to the strength of such samples as a result of chemical reaction. Data are available from the literature, however, which bear directly on the question of strength gains, and hence reactivity, in soils treated with amounts of lime below the lime retention point.

The results of our recent experimental work contradict these hypotheses. Namely, that an amount of lime must be added to a given soil above a given point to maximize these effects (reduction in PI, swell pressure, volume change on drying, permeability, etc.).

(Ho, Handy et ali). For reasons of purification we later substituted "lime retention point" for "lime fixation point." Regardless of the details of the adsorption mechanism, the lime retention point is a valuable concept, particularly useful for engineering purposes. To be sure, the lime retention point slowly changes on curing, probably as a result of localized pozzolanic reaction. Of more practical importance is that the pozzolanic reactions sufficient for cementation do not occur unless lime is added in excess of the lime retention point.

72 Nagaraj — Lime added above the lime fixation point, which is dependent on the BEC, causes a change in matrix and therefore a gain in strength.

LIME MIGRATION

High Pressure Lime Injection

4 Higgins — Results obtained indicate that a good distribution of lime was achieved at depths up to 20 ft. (a relatively heterogeneous, hydraulically placed fill, consisting primarily of soil with high clay content, usually silty to heavy clays). Although there are fluctuations in the pH from sample to sample which probably indicate some non-uniformity of lime distribution.

Miscellaneous

The movement of water (electro-osmosis method) was satisfactory but no appreciable amount of lime was moved.

6 Williams and Handy — Hopefully the lime would slowly dissolve in the ground water and diffuse throughout the soil in the shear zone, changing its plasticity and internal friction.

36 Davidson, Demirel, and Handy — Differences in clay content, clay minerals, density, adsorbed cations, and temperature will affect the diffusion of lime in soils. Water is essential only to provide a medium for lime diffusion. A method for measuring lime migration is described.

74 Roth — Those with an intimate knowledge of soil chemistry state that they have been unable to prove the theory that lime migrates through the soil mass performing desirable functions. Whether it be a true migration or that the lime and the soil immediately surrounding consolidate to give a piling effect, a highly beneficial phenomenon does occur.

LIME STABILIZED SOILS

Gravels, Sands, Silts, and Clays

Gravels

Plastic Index (PI)

24 Herrin and Mitchell — A small percentage of lime lowers the PI and increases the stability of some gravels.

No Improvement

Lime and lime-fly ash when added to Tennessee chert and gravel bases showed no improvement.

Pozzolans

When expanded shale, used as a pozzolan, and lime were mixed with two gravels an improved mixture resulted.

25 Miller and Couturier — In a lime-gravel-fly ash system 4% fines were found to result in:

1. relatively high compressive strengths
2. " " densities
3. low losses in durability tests
4. " water absorption

Sands

19 Mateos and Davidson — Lime stabilized dune sand competes very well with portland cement stabilization in strengths according to freeze-thaw resistance and costs of mixtures.

64 Woods, Berry, and Goetz — Sand soils are too coarse in general to react well with lime alone. A pozzolan is nearly always required.

79	Wissa and Halaby	The quantity of free surface silica is small and thus the amount of cementitious silicate gel formed is limited, further, the rate of extraction of the silica with alkali is slow. Hence, sodium silicates by compensating for this insufficiency are more effective as modifying additives than other sodium compounds.
		Silts
24	Herrin and Mitchell	The more plastic soils are improved to a greater degree than more silty soils.
64	Woods, Berry, and Goetz	Silty soils, with less than 10-12% clay, may be somewhat pozzolanic depending on the minerals present.
		In general:
		1. the stability can be obtained with lime alone. 2. best lime-pozzolan ratio 1:2 3. if the silty soil contains sufficient montmorillonite clay to coat the grains, the mix will not be as pozzolanically active and will benefit from larger additions of pozzolans.
79	Wissa and Halaby	With properties and conditions intermediate of sands and clays, it can be seen that it is relatively of little importance which sodium compound is used, at least in terms of ultimate strength development.
		Sands and Silts
19	Mateos and Davidson	To stabilize sandy or silty soils with lime and fly-ash use 0.5% Na_2CO_3.
54	Zube and Gates	Sands and the coarser silts are generally not benefitted by lime treatment.
55	Dumbleton	Based upon the unconfined compressive strength tests, sandy gravels, well-graded sands, and silty soils could be stabilized with lime.
		Clays
		Kaolinite
		Description
45	McBain	Alternate layers of alumina and hydrate silica. Occurs in tiny flat plates, roughly hexagonal; average size of 0.7 micron in diameter, and 0.05 micron thick; found in "books" or worms.

	Pozzolan
16A Hilt and Davidson	Kaolinite is an effective pozzolanic material.
	Strength
13 Eades and Grim	Kaolinitic soils exhibit strength increases with the addition of the first increment of added lime. Strength begins when the calcium attacks the edges of the kaolinite particles.
	Illite
	Description
45 McBain	From the standpoint of thermal analysis, illite is almost any clay which is not montmorillonite or kaolinite.
	Strength
13 Eades and Grim	Lime added in excess of 4 to 6% accounts for the strength developed in an illite-lime mix.
	Montmorillonite
	Description
45 McBain	According to Jackson, montmorillonite type clay has an ionic atmosphere and a water layer that is 15 Å thick.
50 Norton	Montmorillonite occurs in very fine plate-like particles seldom over 0.05 micron in diameter.
68 Brewer	Montmorillonite is less weather resistant than kaolinite.
	Pozzolan
16A Hilt and Davidson	Montmorillonite is an effective pozzolanic material.
64 Woods, Berry, and Goetz	The pozzolanic strength of montmorillonite gains slowly but it immediately loses its plasticity.

		Strength
13	Eades and Grim	Lime added in excess of 4 to 6% accounts for the strength developed in a montmorillonite-lime mix.
19	Mateos and Davidson	In the montmorillonite-lime-fly ash system the twelve additives (NaOH, Na_2CO_3, $NaCl_2$, etc., see additives to the soil-lime reaction) were detrimental. The strength decrease, in some cases, can be attributed to the excess of Na^+ present and the high alkalinity of the pore fluid.
		In General
30	Laguros, Handy, and Reign	Adding lime to a calcium-montmorillonite clay results in a drastic change. (no logical ion exchange reaction). This has led to the calcium crowding hypothesis.
35	Diamond and Kinter	A lime-montmorillonite reaction did occur resulting in 7.6Å products (calcium aluminate hydrate).
46	Glenn and Handy	X-ray and DTA show unreacted lime remaining in the mixes after two years, and no unreacted mineral in the montmorillonite specimens.
63	Russam and Dumbleton	A 40% montmorillonite soil with a high concentration of NaCl exhibited an unusual sensitivity to rain fall. The soil tended to disperse which resulted in a rapid decrease in strength. The material was stabilized with lime which prevented the clay from dispersing.
70	Sridhara	A Black Cotton soil (montmorillonitic) was successfully stabilized with 8% lime. With additional lime the strength decreased. But with a gumbotil soil (montmorillonitic) this phenomenon was not observed even when as much as 24% lime was added.

Miscellaneous

Strength

12 Davidson, Mateos, and Barnes	It is not necessary for strength purposes to add pozzolans to montmorillonite and kaolinite soils.
21 Remus and Davidson	Dolomitic limes produced a higher immersed strength value when used with illite-montmorillonite soils.

Plastic Limit

16A Hilt and Davidson	The change in PL of the soil-lime mixes was dependent on the type of clay present. It was: 1. greatest with montmorillonites 2. somewhat less with illitic-chloritic clays 3. least changed with kaolinite clays

Mechanism

13 Eades and Grim	The suggested lime stabilizing mechanism for three layer clay minerals (illites and montmorillonites) are: 1. Cation exchange. Existing cations, between the silicate sheets, are replaced with Ca^{++}. 2. Deterioration. The whole structure deteriorates. 3. New Phases. Formation of substantially new crystalline phases.
79 Wissa and Halaby	Fine grained soils have a specific surface and contain considerable reactive silica. Thus, they will lower the pH of the pore fluid when mixed with cement. Hence, sodium hydroxide by appreciably raising the pH will aid considerably in the cementation process.

Lime Depletion

64	Woods, Berry, and Goetz	Clays containing mainly illite, chlorite, vermiculite or kaolinite are all less effective robbers of lime and may be slightly pozzolanic. Improved performance may be attained by adding pozzolan. (e.g., 1:9 to 4:6 lime to fly ash).

LIME STABILIZATION VS CEMENT STABILIZATION

Lime Stabilization

55	Dumbleton	The generated strength is derived from reactions between the lime and the clay fraction of the soil.

Effectiveness

26	Gutschick	Lime is effective in stabilizing highly plastic soils.
55	Dumbleton	Delays between mixing and compaction are not particularly harmful with soil-lime systems but are with soil-cement mixes.
79	Wissa and Halaby	It is seen that $CaO + MgSO_4$ gives higher unsoaked strengths than cement + $MgSO_4$ mixes.

Cement Stabilization

55	Dumbleton	The primary source of strength in cement-stabilized soils is the formation, upon hydration, of cementitious particles which are formed independently of the soil. In addition, lime is released in the course of the hydration of the cement and this lime may react with the clay present in the soil.

Effectiveness

26	Gutschick	Cement is generally restricted to non plastic to low PI soils.
55	Dumbleton	Cement-clay system is more resistant to the action of moisture than lime-clay mixes. There is, however, considerable loss in strength in the cement-stabilized clay.
56	Sherwood	Cement stabilized sand mixtures containing Ca, Mg or Na sulphates were found to be stable when immersed in water even after one year. This was not so when lime was used.
75	Roads and Streets Magazine	Cement treatment was effective for sandy soils and less favorable when used to stabilize heavy clays.

Miscellaneous

38	Arman and Saifan	The loss of compressive strength, durability, and density due to delayed compaction can become so great in intensity that any physical improvements to be derived from the addition of portland cement to the mix are nullified.
51	Peck, Hanson, and Thornburn	Cement grout injection is limited to: 1. soils which are relatively homogeneous 2. " " " " unstratified 3. " whose grain size are not too small (not appropriate for soils much finer than coarse sand).
56	Sherwood	Cement or lime stabilized clay mixtures containing Ca, Mg or Na sulphates disintegrates in a few days after being immersed in water.

ORGANIC MATTER

Determination of Organic Matter Content

79	Wissa and Halaby	To determine the amount of organic matter present, air dry soil passing No. 200 sieve (does not include large fibers and roots) was treated with a known quantity of $K_2Cr_2O_7$ plus H_2SO_4 solution. Any organic matter was thus oxidized and the amount present was calculated from the amount of unreacted $K_2Cr_2O_7$ which was titrated with $FeSO_4$ solution. The organic content is expressed as a percentage of the dry weight of the soil.

Deleterious

55 Dumbleton — Experiments with lime led to no improvement with organic soils which were unsuitable for treatment with cement.

58A Thompson — The presences of substantial amounts of organic carbon (more than 1%) adversely affected the lime stabilization reaction.

79 Wissa and Halaby — The high organic content (2.5%-14%) and plasticity of these soils are usually deleterious with respect to chemical stabilization.

Strengths After Lime Treatment

18 Mitchell and Hooper — The presence of organic matter in the soil accounted for a slight decrease in the strength of the treated and untreated soil.

56 Sherwood — In this investigation it was found that with many soils, particularly those containing organic matter, the addition of sodium sulphate resulted in a considerable increase in the strength of the cement-stabilized soil, although with a few soils a reduction in strength was observed.

58B Thompson — Lime-soil bonding is influenced by organic matter and exchangeable cation status.

Organic matter adversely affected the strength producing pozzolanic reaction.

It is possible that certain soil profiles (A & B horizon with a large percentage of organic matter) cannot be strengthened by lime treatment.

Miscellaneous

14 Ladd, Moh, and Lambe — In an organic soil-lime system, both the soil silica and the organic matter are competing for calcium ions.

Moreover, the addition of most alkali additives not only solubilizes the soil silicates, but also intensifies the organic activity.

The low strength of the 80% illite - 5% kaolinite and 5% montmorillonite - lime mixture can be attributed to the organic matter (7%) which "complexes" lime, and the swelling during curing and soaking tend to rupture cementitious bonds.

37 Taylor	A fairly, stiff unstable bluish clay containing 8 - 12% organic matter, 30 - 40% water, and .2% NaCl was stabilized with hydrated lime (3%).
79 Wissa and Halaby	Adding NaOH to the soil-cement system increase the pH which tends to activate the organic matter to the detriment of the cement gel.
	The calcium ions are absorbed by the organic matter (the phenolic or carboxylic constituents) and thus the calcium ion concentration is reduced to below the necessary amount for calcium silicate precipitation (soil-cement system). The addition of an alkali will only encourage the absorption of calcium ions. However, in the presence of sulfate the pH is lowered and the organic matter remains inactive, and the benefit of sodium ions can thus be achieved.

pH

Sensitivity

Yes

35 Diamond and Kinter	The lime adsorption reaction is uniquely dependent on pH of the suspension.
36 Davidson, Demirel, and Handy	A minimum pH of approximately 10.5 was necessary for a pozzolanic reaction.
45 McBain	The Base Exchange Capacity of clay has a definite meaning only if the titration refers to a definite pH.

But Not Always

3 McDowell and Moore	Many types of soils react favorably to lime stabilization regardless of pH.
67 Chemical Abstracts	The exchangeable H^+ played a very minor role, regardless of the acidity of the soils.

High pH Levels

Determination

44 Zolkov	The higher pH readings for NaOH should be treated with caution due to the difficulty of true pH determination of the solution with such a high concentration of Na^+.

Lime Requirement

The large amounts of lime required to bring the pH of the soil slurry to 12.6 is remarkable. The lime concentration at this pH is about 8 gm/100 gm. of H_2O, whereas the lime's solubility is less than .1 gm/100 gm H_2O.

Mechanism

14 Ladd, Moh, and Lambe

Adding lime to the soil increases the pH of the pore water and this facilitates the formation of a cementitious gel (calcium silicates and/or aluminates) by increasing the reactivity of the surface silica.

The calcium ion concentration is suppressed by adding NaX (where X is OH^-, SO_4^{--}, CO_3^{--} or AlO_2^- .... the common ion effect) which retards precipitation of calcium silicate. The Na^+ reacts with the soil to form a soluble silicate. Therefore, soils should be analyzed for their potential reactive silicate content and then the proper amount of Na^+ added for the production of Na_2SiO_3. Soils with low amounts of reactive silica (sands and silts) do not provide sufficient silica (or aluminate) to react with lime.

44 Zolkov

Adding NaCl or $CaCl_2$ generally causes a progressive decrease in pH.

79 Wissa and Halaby

However*, as the lime reacts with the "gunk"**, the pH drops, and a drop in pH tends to promote the hydrolysis of the $C_3S_2H_x$ to form CSH. The CSH is beneficial if it has been formed by the reaction of the lime and soil particles, but it is detrimental when it is formed at the cost of the formation of the $C_3S_2H_x$ whose strength generating characteristics are superior.

*Refers to Soil-Cement Reactions.

**A small but important fraction of the silica and alumina occurs in an amorphous highly reactive, hydrous state on the particle surface.

Pozzolanic Reaction

1 Davidson, Mateos, and Katti

The decrease in pH of the mixture with time is presumably due to the lime being used up in the pozzolanic reaction.

Silicate Solubility

58B Thompson

The solubility of soil silicate is greatly increased at high pH (12.3).

Miscellaneous

28 Sheeler, Picaut, and Demirel

If the soil is salt free, the resistivity correlates with density. Whereas if the soil contains a known salt, the resistivity correlates with the soil properties. In this case, the determination of the salt content can be made using resistivity.

35 Diamond and Kinter

(Ho, Handy et ali). It is interesting that in this region the pH has stabilized at 10.5, which other evidence suggests is the threshhold for pozzolanic reaction.

44 Zolkov

The changes of pH with time (based of course on the initial pH determination) can be related to the amount of lime absorbed.

45 McBain

Marshall and Krinbill refer to colloidal particles of clay as colloidal electrolytes on account of their charges and conductivity. A hydrogen clay paste has an appreciable conductivity and a pH between 2 and 3.5; whereas, if it is allowed to settle, the supernatant water is approximately neutral and exhibits very little conductivity.

58A Thompson

Broadly speaking, a pH greater than approximately 7, the Ca/Mg ratio in excess of about 1.5 with larger-than-average amounts of exchangeable sodium, and poor natural drainage were indicative of good lime-reactivity.

61 Kleinfelder

The cation portion of a chemical stabilizer appears to be the main factor effecting stabilization, along with the pH of the solution.

Additives which have a high pH factor or large hydrated cations should not be used as stabilizers.

79 Wissa and Halaby	To a 2:1 aqueous solution by weight of dry soil was added enough $CaCl_2$ to give a molarity of 0.01, and sufficient time was allowed for complete flocculation to take place. The pH of the supernatant was then measured with a pH meter which had been balanced with two known buffer solutions. (pH4 and pH7).

THE POZZOLANIC REACTION

Statements

35 Diamond and Kinter	Pozzolanic reactions require lime in excess of the lime retention point for sufficient cementation.
	The strength of lime-pozzolan systems depends somewhat on the kind of cementing agent formed and also to a great degree on the "gel/space" ratio.
64 Woods, Berry, and Goetz	In general, the pozzolanic reaction is sensitive to the class of lime used. But when the only desired change is in soil plasticity the class of lime used is relatively unimportant.
72 Nagaraj	The lime-pozzolanic reactions main gain-in-strength with time is due to the precipitation and cementation of the $CaCO_3$ (from CO_2 in the water), and the complex silicious and aluminous gels of calcium.
79 Wissa and Halaby	$Ca^{++} + 2(OH)^- + SiO_2$ (Soil Silica) = CSH $Ca^{++} + 2(OH)^- + Al_2O_3$ (Soil Alumina) = CAH

Reaction Products

2E McDowell	Combination with lime forms stable gels whose stability is not impaired by leaching.
16A Hilt and Davidson	Lime-montmorillonite (or kaolinite) produces a cementing material equal to or greater in strength producing qualities than products of the reaction of lime with fly-ash.
58B Thompson	The lime-soil pozzolanic reaction occurs between soil silica and/or alumina and lime to form various cementing agents. Organic matter adversely affects the strength producing pozzolanic reaction.

64	Woods, Berry, and Goetz	Optimum moisture of the final product of the pozzolanic reaction depends upon the percentage of pozzolan in the original mixture.
		Miscellaneous
2D	McDowell	Using a base as an open surface road prohibits the development of the pozzolanic reaction.
24	Herrin and Mitchell	It appears that, to date, no known test on the natural soil can accurately indicate the compatibility of the soil with lime. Base exchange capacity, the pH of the soil, nor the plasticity characteristics seem to be satisfactory indicators. The only positive method that will indicate if lime by itself will improve a soil is a test of the lime-soil mixture.
36	Davidson and Demirel	The detection of a pozzolanic reaction (providing no carbonate is present) is noted in the change of the Ca^{++} content of the HCl leachate from soil-lime-water system which was previously leached free of dissociable Ca^{++} with a KCl solution.
57	Pacific Rd. Builder & Eng. Review	The worse the pozzolan (clay type) soil, the greater its improvement with lime treatment.
64	Woods, Berry, and Goetz	Well-graded mixes containing binder material such as clay or calcium carbonate (caliche) may gain enough added strength with 2-4% lime.

SAFETY

Potential Danger

Quick Lime - "Hot Lime"

39	Amer. Rd. Builders Assoc.	Quick lime is more dangerous to use and much more caustic than hydrated lime. This lime can produce severe burns.
41	U.S. Dept. of Commerce	Quick lime does present some hazards in handling, but the hazards can be minimized by the proper precautions.
59	Street and Highway Manual	Quick lime can produce severe burns quickly when in contact with moist skin. It is considerably more dangerous to use than hydrated lime.

Hydrated Lime

Hydrated lime is not dangerous to work with provided a few simple precautions are exercised. Some general points are:

1. The "severe burns" danger is remote
2. It is desirable to prevent skin contact
3. Avoid prolong contact with a perspiring worker's skin, especially where the skin is also chafed by tight clothing.

Body Protection

Clothing

Shirt

39 Amer. Rd. Builders Assoc.

Wear at least one long sleeved shirt. Do not roll up sleeves!

Shoes

Wear high tops.

Trousers

The trousers legs should be tied over shoe tops.

Hat

A hat or cap should be worn.

Gloves

Wear a gauntlet type glove.

Face Mask

75 Roads and Streets Magazine

Worker should wear a face mask.

Protective Cream

39 Amer. Rd. Builders Assoc.

Apply a protective cream to exposed areas of the body. Some of the creams used are: Vaseline and West's #311 cream.

Eye Protection

Wear safety glasses (or goggles) with side shields.

Lung Protection

Although inhalation of some lime dust is not injurious mouth and nose protection in the form of a lightweight filter mask is a "must."

Bathing

After work, bathe or shower to cleanse the body.

First Aid

Skin Burns

1. Wash burn area with soap and water to remove the lime.
2. Apply a standard burn ointment.
3. Keep burn area bandaged during healing to prevent infection.

Eyes

1. Hold eyes open and flush with water immediately. Too much water cannot be used! (Plastic eye wash bottles are ideal for this use).
2. Report all burns (especially eyes) to an MD.

Caution!

Sensitive Skin

59 Street and Highway Manual

Some people with particularly sensitive skin have developed forms of skin irritation (dermatitis) through prolonged contact.

Hot, Humid Weather

Hot, humid weather conditions tends to heighten the caustic effect of hydrated lime on worker's skin.

SLOPE STABILIZATION

6 Williams and Handy

A fill containing for the most part calcarious, montmorillonitic loess and glacial till was placed on a Pennsylvanian shale hillside sloping 20-30%. The earth began to move and continued to slide for three years. A discreet shear zone was identified and seeded with quick lime plus water for hydration. Hopefully, the lime would slowly dissolve in the groundwater and diffuse throughout the soil in the shear zone changing its plasticity and internal friction. Two months later it was observed that soil shearing strength was increased 50% above average and a pozzolanic cementation reaction was indicated. Two years later the shearing strength increase was 100%. Twenty tons of lime were used to stabilize two residential lots.

40 Berkland — Consideration of these data indicates the possibility that certain slopes in the Franciscan formation which owe their instability to the presence of swelling vermiculite may be chemically stabilized. The introduction of a potassium salt solution through techniques of spraying or infiltrating could convert the vermiculite into an inoffensive, mica-like clay which would resist seasonal volume changes.

42 Cross — "Liquid nitrogen is mighty cold at -320 degrees below zero. But it proved a hot item for Tomaro Construction Co. when they used it to solidify bad ground that threatened to louse up their sewer job in hometown Milwaukee. The material that was stabilized was a running silt, and soft wet clay. The apparatus used for the tunnel job is simple and easy to install."

45 McBain — Heaving shales have given trouble to tunnel building and drilling. The cause of this swelling is due to the absorption of water from drilling mud and exposed surfaces. Calcium or other polyvalent ions can minimize this effect.

76 Litvinov — From the engineering and economical standpoint, deep thermal treatment of soils should be recommended:

1. To consolidate loess soils in foundations.
2. To correct differential settlement.
3. To prevent landslides.

STRENGTH

Soils

Sand

24 Herrin and Mitchell — The strength of relatively clean river sand showed little improvement by adding lime alone. But when lime-molasses was used the strength was noticeably increased.

Silt

31	Walker and Karabulut	Decreases in unconfined compressive strength due to freezing and thawing are much less in lime-silt mixtures than in lime-clay mixes.

Clay

Base Course

12	Davidson, Mateos, and Barnes	Strength gains (clay soils-lime) are too slow to meet base course requirements. Possible accelerators are chemical additives or heat.

Lean Clay

41	U.S. Dept. of Commerce	Results of Laboratory Evaluation Tests of a lean clay are:

	% Lime Added		
	3	5	8
Quick lime	95*	137	171
Hydrated	67	85	95

Plastic Clay

14	Ladd, Moh, and Lambe	Plastic clay-lime mixtures may require many months, or even years, to develop their ultimate strength.

Fat Clay

44	Zolkov	The PI does not necessarily reflect the mechanical properties of this soil. It is no reflection of the compressibility or swelling and certainly does not reveal the high water stability of the clay nor its strength.

Pozzolan Systems

In General

35	Diamond and Kinter	The strength of lime-pozzolan systems depends somewhat on the kind of cementing agent formed and also to a great degree on the "gel/space" ratio.

*Untreated (control) gave 21 psi, all strength values in psi.

58B	Thompson	The major source of strength increases stems from the lime-soil pozzolanic reaction.
72	Nagaraj	The gain-in-strength with time is mainly due to the lime-pozzolanic reaction.

Shear Force

48B	Eckel, Baker, and Marshall	If, as is usually the case, the slip-surface is curved (Landslides), the bulk of the motivating forces will come from the area that overlies the steepest portion of the slip-surface. One solution: increase in the resisting force can be accomplished by techniques that increase the internal shearing resistance of the moving mass itself. Actually, the principal effect of drainage may well lie in the increase of the shearing resistance rather than in the nominal decrease in weight, hence, of motivating force. Most of the shearing within a soil or rock mass is attributable to frictional resistance and cohesion.

Conditions

Additives

1	Davidson, Mateos, and Katti	Acid salts ($AlCl_3$) may impede development of strength.

Lime Percentages

14	Ladd, Moh, and Lambe	The percentage of lime added above the optimum level is often relatively ineffective.
		Quicklime (1 to 5%) added to 4 very wet soils ranging from silt to plastic clay increase the strengths 3 to 10 fold within two hours.

Temperature

19	Mateos and Davidson	Strength increases brought on by chemical additives are very critical at temperatures close to climatic.
24	Herrin and Mitchell	Cool or cold temperatures are not desired conditions for producing high strengths in lime-soil systems.
55	Dumbleton	The rate-of-gain in strength for lime-soil and cement-soil systems is greater at higher temperatures.

Maturity

1	Davidson, Mateos, and Katti	An increase in long term strength results from using some weak bases [$Al(OH)_3$, $Fe(OH)_3$] in activating the Ottawa sand-lime-flyash system.
		Sodium tetraphosphate greatly benefitted early strength. It may react with lime to produce complex phosphate cementation products which supplement those produced by the pozzolanic reaction.
3	McDowell and Moore	Mixes which are hardest at an early age are not necessarily the best because some of the differences in strength may be due only to the rate-of-setting having been speeded up.
17	Anday	The strength of lime stabilized soils is a function of maturity when subjected to field curing.
22	Ruff and Davidson	Upon aging, a Kansas till, with 6% calcitic lime and any one of 5 powered sodium silicates, decreased in strength.

Testing

Freeze-thaw

31	Walker and Karabulut	A smaller percentage of strength was lost during freezing and thawing when the lime content was increased up to 10 percent (both clay-and silt-lime systems).

R-Value

53	Zube, Gates and Hatano	The R-value of some recompacted lime treated soils may be lowered by as much as 50. The R-value of a soil before lime treatment may be 5, but after the treatment frequently may be well over 60.

Soak

14	Ladd, Moh and Lambe	The soak strength of the lime stabilized soil increased after humid cure periods.
		The effect of sodium compounds on the soak strength (compressive) of 7 organic clay-lime mixtures showed that none of the sodium additives improved the strength.

18	Mitchell and Hooper	Soaked strengths of lime treated samples showed improvement over the untreated soil; being increased as much as 7-fold by lime treatment. The improvement in soaked strength follows directly from the decrease in swell afforded by lime treatment.
19	Mateos and Davidson	Immersed strengths of Ottawa sand-lime-flyash systems may be increased several times by adding a small amount of chemicals.
21	Remus and Davidson	The immersed strengths of montmorillonite and illite soils are higher when a dolomite monohydrate lime is used than when a calcitic hydrated lime is used, whereas when kaolinite soils are stabilized there is no consistent difference between the limes used.
24	Herrin and Mitchell	There is little water soak strength increase when lime-molasses was used in stabilizing a clean river sand.
		Triaxial
32	Laguros	Strength benefication of lime-montmorillonite clay and soil-lime-chemical seems small judging from the unconfined tests, whereas the triaxial test indicates greater improvement.
		Miscellaneous
2E	McDowell	Laboratory strengths may indicate a Class 1 mix but the same clay-lime mix may not obtain such strengths in the road due to delayed mixing, compacting and weathering. Cores cut from old roads consisting of old, lime-granular soil mixtures show that field strengths are higher than are found from laboratory tests on specimens up to 60 days old.
17	Anday	Accelerated laboratory curing can predict the unconfined compression strength for field cured specimens at summer temperature. The strength will be a function of the maturity.
18	Mitchell and Hooper	The delay between mixing and compaction was detrimental in terms of density (by as much as -8 pcf), swell and strength (by as much as 30% for a 24-hr. delay).
23	Dawson and McDowell	By some process of autogenetic healing, specimens which were previously broken in the cohesiometer developed considerable strength following a period of recurring.

35 Diamond and Kinter — The rapid "ameliorating" effects of lime on the properties of plastic soils are documented from the literature, and the distinction between these short-time effects and the long-time cementitious reactions responsible for the development of strength is noted. The cation crowding hypothesis is rejected as an explanation of the ameliorating effects. New results summarized show that the cation crowding is more accurately described as physical adsorption of calcium hydroxide on the clay surfaces.

39 Amer. Rd. Builders Assoc. — The "set" was usually slightly faster with the lime-fly ash mixture than with the lime-soil mix.

50 Norton — There is much speculation about dry strength. The most reasonable explanation appears to be the van der Waals forces.

SWELLING SOILS

Methods of Measuring Swell

8 Davidson and Page —

1. The difference in adsorption of H_2O and benzene.
2. Measuring the swell pressure.
3. Method based upon swelling volumes. (Swell pressure method is more desirable than swelling volume method).

Factors

Osmotic Pressure

1 Davidson, Mateos, and Katti — Osmotic pressure is the prime cause of soil swelling.

61 Kleinfelder — Osmotic pressure. The difference between two curves (two Moisture-Density Curves... the first curve was the soil-water system, while the second curve was the soil-$CaCl_2$ solution system) can be considered as the swelling caused by osmotic pressure.

To Change the Swelling

To Decrease

58B Thompson —

1. Replace the existing cation with Ca^{++}.
2. Pozzolanic reaction products resist volumetric expansion.

		To Increase
8	Davidson and Page	1. Remove iron oxide 2. Remove organic matter 3. Adsorption of soil conditioners
18	Mitchell and Hooper	Some tests have shown a consistent trend for a slight decrease in strength and increase in swell to occur with both treated and untreated samples when the curing time is increased from 35 to 60 days. The cause of this behavior has not yet been established; however, the effects of the organic matter or bacteriological factors are suggested as possibilities.
		Miscellaneous
1	Davidson, Mateos, and Katti	Some clays are not structure sensitive. Therefore, the normal reduction of soil swelling expected of a dispersed clay* cannot be assumed, even when the soil is compacted wetter than optimum moisture.
40	Berkland	Add KCl to a water suspension of vermiculite (Franciscan formation) and it becomes nonswelling.
45	McBain	If the external ion of montmorillonite is Na, the result is a highly swelling clay of the Wyoming bentonite type. If it is hydrogen, Ca, Mg or other polyvalent ion, the clay coagulates and swells very little. All clays swell in water to a certain degree. There is no direct relation between swell and fineness of particles. A sample of Wyoming "swelling" bentonite and another of Missouri "nonswelling" bentonite, on being compared following base exchange, each swell in the following increasing order. Mg^{++}, Ca^{++}, H^{+}, K^{+}, NH_2^{+}, Na^{+}
62	White, Baptist, and Land	Montmorillonite is the most sensitive clay mineral because it swells in the presence of water.

*It is important to determine in the field whether or not a clay is dispersed.

TEMPERATURES

In General

1 Davidson, Mateos, and Katti

"Heat is known to be a good activator for the lime-fly ash (pozzolanic) reaction...." But since high temperature curing of road base is not economical with presently (1959) available fuels, a more practical alternative for activation of the lime-fly ash reaction would be with trace chemical additives.

12 Davidson, Mateos, and Barnes

Accelerators of hardening of montmorillonitic clay soil are:

1. Heat
2. NaOH - small amount (1-2% optimum)

20 Wang, Davidson, and Rosauer

The calcining temperature during lime production is important in lime stabilization.

75 Roads & Streets Magazine

Specifications. Manipulation of lime into the soil should take place only when the temperature is above 40°F.

24 Herrin and Mitchell

Warm temperatures and a long time period

1. yields greater strength and quality
2. almost necessary in adequate curing

At Low Temperatures

69 Iwamoto and Sudo

NH_4Cl played an important role in promoting the chemical reaction by lowering the reaction temperatures and giving rise to a specific assemblage of reaction products.

At Ordinary Temperatures

35 Diamond and Kinter

Temperature and kind of clay determines the end products. At room temperature:

1. Calcium silicate hydrate ...(usually a tobermorite gel).. and,
2. Calcium aluminate hydrate forms (probably an impure tetracalcium aluminate hydrate)

58B Thompson

Relative slow pozzolanic reaction occur at 75°F. (Faster at higher temperatures).

At Higher Temperatures

24	Herrin and Mitchell	Elevated temperatures accelerate the pozzolanic reaction.
35	Diamond and Kinter	At slightly above room temperature a cubic tricalcium aluminate hexahydrate forms (instead of the tetracalcium aluminate hydrate)
55	Dumbleton	"The effect of high temperatures in producing accelerated hardening probably accounts in part for the success of soil-lime in areas having hot climates, such as Northern Rhodesia and Texas. Lime-soil and cement-soil reaction exhibit a greater rate-of-gain in strength at higher temperature.

TOBERMORITE GEL

Description

66	Engineering (Great Britain)	The calcium silicate hydrate, because of its similarity to the natural mineral tobermorite has been called "tobermorite gel," and this gel is the most important constituent of hardened portland cement.

Pastes of di and tricalcium silicate set and harden, qualitatively, in the same way as do pastes of portland cement.

It's the hydrate form which is called "tobermorite gel." All tobermorites, natural or synthetic, are layer crystals having some similarities to vermiculite.

Properties

When tricalcium silicate is ground to 10 micron (similar to the fineness of portland cement) the resulting surface area is about a thousand times smaller than the hydrated form. The relatively large area of the hydrated form contributes greatly to the properties of the paste.

The adhesion of the tobermorite gel particles to each other and to other bodies is responsible for the strengths of hardened pastes of tri-calcium and dicalcium silicates.

Mechanism

Aging

Tricalcium silicate plus water, at room temperature, sustains a reaction that will go on for a year, depositng a calcium silicate hydrate. Dicalcium silicate reaction is similar though more involved

pH

26 Gutschick

Under the conditions of high pH, the lime begins eating into the clay particles, destroying the structure and releasing silica and alumina ions. Then, in the presence of moisture, hydration occurs forming calcium silicate hydrate (similar to tobermorite) and to a lesser extent calcium silica aluminates (similar to hydrous garnets)

Varying Conditions

35 Diamond and Kinter

Tobermorite may be synthesized readily by hydrothermal means, but its occurrence in lime-soil reaction products produced under normal atmospheric conditions is extremely unlikely.

66 Engineering (Great Britain)

When lime and tricalcium silicate paste (minimum water) is prepared, the water becomes saturated with calcium hydroxide within minutes forming a tobermorite gel. But when an excess of water is used, a calcium silicate hydrate forms which is not a tobermorite gel.

The production of tobermorite is dictated by CaO/SiO_2 ratio in the calcium silicate hydrate which depends upon the final concentration of the lime in solution. This ratio ranges from 0.8 (at low lime) to 1.5 (at high lime concentrations).

TABLE I

Action of Chemicals on Soils

Chemical	Reference	Flocc	WP[1]	Atterberg Limits PI	LL	PL	SL	Remarks
Inorganic								
Various salts	35	x						
Acids	35	x						
$Al(OH)_3$	1		x					
$BaCl_2$	27[2]				lowers		small	
$BaCO_3$	27			Increases	Increases	lowers		Highly plastic[4]
$CaCl_2$	1, 27, 59, 61, 79	x			lowers		small	High water surface tension
$Ca(OH)_2$	27			Increases***			Increase	Friable[4]
$CuSO_4$	27	x						
$FeCl_3$	27, 61, 77	x						Porous[4]; Reduces frost heave
$Fe(OH)_3$	1		x					
KCl	27			lowers****				
$K_2Cr_2O_7$	27				lowers*	lowers	small	
KOH	27			Increase**				Friable[4]
$MgCl_2$	27				lowers		small	
$MgCO_3$	27			Increase	Increase	lowers		Highly plastic[4]
NaCl	27, 59						Increase	Forms Colloidal Binder
NaOH	27			Increases**			Increases	Friable[4]
Na_2CO_3	27			Increase	Increase			Highly plastic
Na_2SO_4	27			Increase	Increase			Acts as dispersing agent

[1] WP = waterproofing agent

[2] (all Ref. 27) with expansive soil which may be montmorillonite or montmorillonite-illite

*very marked at 10% **at lower % ***below 1% ****beyond 2%

[3] Beyond 3% not possible to run LL & PL [4] Final soil condition

TABLE I (contd)

Action of Chemicals on Soils

Chemical	Reference	Flocc	WP[1]	Atterberg Limits PI	LL	PL	SL	Remarks
Inorganic (contd)								
$Na_4P_2O_7$	77							Reduces frost heave
Na_2SiO_3	27		Increase					Dispersion[3] Highly plastic
$(NH_4)_2HPO_4$	27							NH_3 causes porosity[4]
$(PO_4)^{---}$	27						small	
Phosphoric Acid	64							Forms insol phosphates /cations in clay
$(SO_4)^{--}$	27						small	
Silicones	64		x					Expensive
Spent sulphite liquor	9							
Organic								
(Rosin) Abietic acid	64		x					Coats soil grains
Acrylonitrils	64		could be					Reduce erosion on embankment slopes. Acts as resinous glue.
Alcohols	35	x						
Arquat 2HT	39		x					Especially clays
Bitumen	65							
Ketones	35	x						
SC-100	59							Reduces surface tension [illegible] accelerates moisture penetration (adobes, clays silty loams, hardpan, etc.

TABLE 2

Action of Lime on Soils

Soil & Ref.	Strength Increase	Reaction Product	Remarks
Gravel			
24	No		But often can be improved/ pozzalan
Sand			
19	See remarks		Trace montmorillonite present. Strength of dune sand comparable to portland cement stabilized dune sand.
55	Based upon cohesion test		Sandy gravels & well graded sands
64	See remarks		Pozz. required; needs more than lime alone
79	Yes, but		Use additive (e.g. sodium compounds)
Sand & Silt			
19	See remarks		Use 0.5% Na_2CO_3/Flyash
54	" "		Generally not benefitted
Silts			
5	Yes	Hydrophobic	Also immersed water strength greatly improved (1% lime)
14	Yes		5% lime + sodium sulfate
24	See remarks		The more plastic soils improved more
55	Based upon cohesion test		Could be stabilized
64	Somewhat		If less than 10-12% clay. Best lime-pozz. Ratio 1:2
Silty Clay			
15			PI decreased. PL slight incr. (9%, 9%)[1]
Clay			
General			
16			Illitic - chloritic soil. PL Moderately increased
24			PI lowered using small amounts of lime.
56 (London Clay)		Probably ettringite if insufficient water is present.	Clay contained 2% calcium sulphate which disappeared following water immersion.

1 Double application at indicated percentages

TABLE 2 (contd)
Action of Lime on Soils

Soil & Ref.	Strength Increase	Reaction Product	Remarks
Kaolinite			
13	Yes		With the 1st increment of added lime.
14	Yes		5% lime & sodium sulfate.
16A	Yes		E. P.[2], Produces a cementing material.
21	See remarks		High calcitic hydrate Lime or dolomitic Type N yielded similar water immersion strength.
35 (calcined)	Yes	Quarternary gehlenite Hydrate, C_2AS_x	Also called "Strathings Compound."
		1. C-S-H(I)+C_2AH_6	@ 60° C
		2. T.G.[3]+(7.6Å C-A-H)	@ lower temperature
Illite			
13	Yes		Increase beings above 4-5% lime. Soil: 80% illite, 5% montmor. 5% kaolinite. Na_2SO_4
14	No		Had ineffectual to harmful effect on soaked strength.
35		T.G.[3]+(7.6Å C-A-H)	
Montmorillonite			
13	Yes		E. P.[2], Increase begins above 4-6% lime.
16A	Yes		Large increase in plastic limits.
19	No		when NaX(where X = Cl, OH, CO_3, meta silicate) is present.
35		1. C-S-H(I)	@ 60° C.
		2. T.G.[3]+ (7.6Å C-A-H)	@ lower temp.
		3. T.G.[3]+ C-S-H(I)+C_4AH_{13} + possible C-S-H(II)	@ room temp.

2 = effective pozzoloanic material   3 = tobermorite gel.

TABLE 2 (contd)
Action of Lime on Soils

Soil & Ref.	Strength Increase	Reaction Product	Remarks
Montmorillonite (contd) 44 (smectite)		NH_3 evolved upon addition of NaOH	(Dioctahedral). A fat clay 10% calcite + 3% organic matter + very little kandite..
64	Yes, Slowly		E. P.[2], PI decreases.
Bentonite 16B		Similar to $4CaO_x.Al_2O_3.13H_2O$	According to "d" spacing.
30		1. Ca absorbed outside clay particle Ca-bentonite-$Ca(OH)_2$	1% lime added
		2. additional Ca^{++} attached outside	2% or 4% lime
35		No heat change	A calcium bentonite.
Gumbotic 19	No		Effect Nil to harmful. Strength much lower.
70	No		Did not behave like black cotton soil.
Alluvial 19	No		Strength much lower.
Black Cotton Soil 70	Yes		8% lime gave increase More than 8% gave decrease.
Mont. & Illite 14	No		Soil: equal parts illite, montmor., feldspar, quartz. Sodium sulfate harmful to soaked strength.
21	See remarks		Using high calcium lime, water immersion strength was lower. Using dolomitic type N., strength was higher.
Other Soils 14	No		Sodium sulfate additive was harmful to soaked strength 90% quartz, 10% bentonite sample.
35		T.G.[3]	
Mica 35		T.G.[3] + 7.6Å C-A-H	

TABLE 2 (contd)
Action of Lime on Soils

Soil & Ref.	Strength Increase	Reaction Product	Remarks
Pyrophyllite			
	35	TG[3] + 7.6A C-Å-H	
Loam (mostly allophane)		Gehlenite hydrate and 7.6Å C-A-H	Normal temperature.
		C_3AH_6 & a quarternary phase	Higher temperature.
Gypsum		Ettringite (cement bacillus)	Excellent stabilization.
		Calcium sulfo-aluminate	
Loams	15		PI const. P. L. slight incr. (9%, 9%)[1]
Clay Loam	15		PI slight decr. P. L. const. (9%, 9%)[1]
Sandy Loam	15		PI, PL const. (6%, 12%)[1]

TABLE 3

BASES

CHEMICAL ADDITIVES TO THE LIME-SOIL MIXES

Chemicals	Formula	Reference	Some Remarks
Magnesium hydroxide	$Mg(OH)_2$	20	appreciable amounts lower strengths
Potassium hydroxide	KOH	1	Note 1
Sodium hydroxide	NaOH	1	Note 1
		12	1-3%, most successful-doubled the strength
		14	provided additional silica.* ineffectual/clayey silts
		19	appeared most promising. **Note 1a.
		32	does not improve consistency properties once lime is the main-stabilizing agent. Increased weather resistance.
		70	promising in improving strength

Note 1 a. Additive to an Ottawa sand-lime-flyash mixture
b. 1% may not be economical
c. 0.5% more desirable treatment level

*or made the silica more reactive and controlled the rate of reaction between the lime and the silica.

**1. soil-lime-flyash systems
2. beneficial in mixtures of friable materials
3. detrimental in mixtures of montmorillonitic clay soils

TABLE 3 (contd)

CHEMICAL ADDITIVES TO THE LIME-SOIL MIXES

Chemical	Formula	Reference	Remarks
Basic Salts			
Lithium Carbonate	Li_2CO_3	1	Note 1
		19	Note la. May have some catalytic effects as NaOH
Potassium Bicarbonate	$KHCO_3$	1	Note 1
Potassium Carbonate	K_2CO_3	1	Note 1
Sodium Bicarbonate	$NaHCO_3$	1	Note 1
Sodium borate	$Na_2B_4O_7 \cdot 10H_2O$	1	Note 1
Sodium carbonate (soda ash)	Na_2CO_3	1	Note 1. Most promising trace activator
		12	Gave inconsistent results
		14	Provided additional silica.* Very effective/kaolinite, quartz-bentonite, but did not improve quartz-lime mix.
		19	Most effective.**. Note la For sandy or silty soils Most effective accelerator
		64	Trace amounts are effective
		70	Promising
Sodium sulfite	$Na_2SO_3 \cdot 7H_2O$	1	Note 1
Sodium phosphate	$Na_3PO_4 . 12H_2O$	12	Decreased strength
		19	Not the most effective. Note la. Used with Ottawa sand-lime-flyash
Alkali metal compounds		79	Compounds showing increased strength include hydroxides and many salts. Sodium compounds found effective, Formed insol. salts with Ca. Effectiveness of Na compounds decreased with increased plasticity and organic matter.

NEUTRAL SALTS CHEMICAL ADDITIVES TO THE LIME SOIL-MIXES

Chemical	Formula	Reference	Remarks
Lithium Chloride	$LiCl$	1	Note 1
Lithium Floride	LiF	1	Note 1
Lithium Nitrate	$LiNO_3$	1	Note 1
Lithium Sulfate	$LiSO_4 . H_2O$	1	Note 1
Potassium Chlorate[a]	$KClO_3$	1	Note 1
Potassium Chloride	KCl	1	Note 1
Potassium Dichromate[a]	$K_2Cr_2O_7$	1	Note 1
Potassium Permanganate	$KMnO_4$	1	Note 1
		19	Note 1a. May oxidize the carbon in flyash
		70	Promising. Used with 6% lime.
Sodium Chloride	$NaCl$	1	Note 1
		19	* *
Sodium Dichromate[a]	$Na_2Cr_2O_7 . 2H_2O$	1	Note 1
Sodium Hypochlorite[a]	$NaOCl$[b]	1	Note 1
Sodium Nitrate	$NaNO_3$	1	Note 1
Sodium Permanganate[a]	$NaMnO_4 . 3H_2O$	1	Note 1
Sodium Sulfate * * *	Na_2SO_4	1	Note 1
		14	Additive increased soaked strength for 2 natural silts and 1 kaolinite but was ineffectual or detrimental to quartz, 90% quartz + 10% bentonite, 5% montmorillonite + 80% illite, and combination of equal parts quartz, feldspar, illite, and montmorillonite. Effective/clayey silt.
		56	Without significant effect. Strength less when immersed in water.

[a]Strong oxidizing agent

[b]In sol'n with 5-6% available chlorine.

***See sulphates in miscellaneous group

TABLE 3(contd)

ACID SALTS

CHEMICAL ADDITIVES TO THE LIME-SOIL MIXES

Chemical	Formula	Reference	Remarks
Aluminum Chloride	$AlCl_3 \cdot 6H_2O$	1	Note 1
		19	Not the most effective used with Ottawa sand-lime-flyash
Amonium Chloride	NH_4Cl	1	Note 1.
Calcium Chloride	$CaCl_2$	1	Note 1. One of the most promising for long term strength
		19	Note 1a. Highly hygroscopic.
		24	Increased weather resistance.
		32	Does not improve consistency properties once lime is the main stabilizing agent. Increased weather resistance.
		70	Promising - 6% lime used.
Calcium Hypochlorite[a]	$Ca(OCl)_2$	1	Note 1
Calcium Sulfate	$CaSO_4$	1	Note 1
		56	**marked benefit effect at constant MC leaked out of specimen. some evidence that ettringite formed.
Chromic Chloride	$CrCl_3 \cdot yH_2O$	1	Note 1
Cobaltous Chloride	$CoCl_2 \cdot 6H_2O$	1	Note 1
Cupric Chloride	$CuCl_2$	1	Note 1
Ferric Chloride	$FeCl_3$	1	Note 1
Ferric Sulfate	$Fe(SO_4)_3 \cdot XH_2O$	1	Note 1
Ferrous Chloride	$FeCl_2 \cdot 4H_2O$	1	Note 1
Ferrous Sulfate	$FeSO_4 \cdot 7H_2O$	1	Note 1
Magnesium Chloride	$MgCl_2 \cdot 6H_2O$	1	Note 1
Magnesium Sulfate		56	Without significant effect. Strength loss on water immersion.
		79	Strengths gained varied 20%-200% and were attributed to formation of Ca-Mg-Silica gel.

TABLE 3 (contd)

CHEMICAL ADDITIVES TO THE LIME-SOIL MIXES

ACID SALTS

Chemical	Formula	Reference	Remarks
Manganous Chloride	$MnCl_2 . 4H_2O$	1	Note 1
		19	Note 1a. Produces effects like $CaCl_2$.
Nickel Chloride	$NiCl_2 . 6H_2O$	1	Note 1
Stannous Chloride	$SnCl_2 . 2H_2O$	1	Note 1
Titanium Tetrachloride	$TiCl_4$	1	Note 1
Zinc Chloride	$ZnCl_2$	1	Note 1

ACID GROUP

Chemical	Formula	Reference	Remarks
Phosphoric Acid	H_3PO_4(85%)	19 64	Note 1a. Some strength inc. Produces insoluble phosphates which behave as cement.
Salicylic Acid	$C_7H_6O_3$	24	Increases weather resistance.

TABLE 3 (contd)

MISCELLANEOUS GROUP CHEMICAL ADDITIVES TO THE LIME-SOIL MIXES

Chemical	Formula	Reference	Remarks
Aluminum Oxide	Al_2O_3	20	A variable in controlling st[illegible]
Asphalt	---	42	Appears suitable for fine-grained soil, combination is stronger, more waterproof than asphalt alone and far less sensitive to variations in compaction WC.
Ethylene Glycol	CH_2OHCH_2OH	1	Note 1
Iron Oxide	--	53	Does not respond well.
Lime-Molasses	--	24	Used with a river sand. 1. Lime alone yielded little strength. 2. Lime with molasses increased strength. 3. When water soaked less increased strength.
Magnesium Oxide	MgO	1	Note 1
		19	Note 1a. May enter pozzolanic reaction.
		20	With SO_2 and R_2O_3* most reliable in evaluating a dolomitic lime. Generally higher strengths with finer crystals.
		64	Accelerated an otherwise sluggish lime-pozzolanic reaction.
Magnesium Carbonate	$MgCO_3$	20	Appreciable amounts lower strengths.
Plaster of Paris	$(CaSO_4)_2 \cdot H_2O$	24	Should not be used.
Portland Cement	--	1	Note 1
		79	Portland Cement and quicklime. Possibly with trace chemicals were most promising systems.
Potassium Biphthalate	$KHC_8H_4O_4$	1	Note 1

[c]Trade name for sodium tetraphosphate (P_2O_5-63.5%; Na_2O 36.0%; H_2O-0.5%)

*$R_2O_3 = Al_2O_3 + Fe_2O_3$

MISCELLANEOUS GROUP : CHEMICAL ADDITIVES TO THE LIME-SOIL MIXES (contd)

Chemical	Formula	Reference	Remarks
Pozzolan	is flyash	12	Unnecessary for strength purposes with montmor. & kaolin soils.
		39	Generally needed with nonplastic soils.
		64	nearly always required for sand soils.
Quadrafos	c	1	Note 1
Sodium Aluminate	$NaAlO_2$	14	Very effective/Kaolinite but did not improve quartz-lime.
Sodium Silicate	--	22	Dry density decreased. Strict controls necessary. Strength decrease depends upon molding MC & type of silicate. Used with 6% calcitic lime.
		64	Reacts with calcium salts to give insoluble calcium silicate cement. Used for sealing leaks in reservoir.
		70	Promising for improving strength. Trace amount used.
Silica A- Sodium meta-silicate enneahydrate	$Na_2SiO_3 . 9H_2O$	14 19	Effective/clayey silts. * *
B- sodium meta-silicate anhydrous	Na_2SiO_2	22	Decr. strength/incr. aging. Stengths using Silica B greater than Silica A at equal molding MC.
C- sodium meta-silicate pentahydrate	$Na_2SiO_3 . 5H_2O$		Best of group using 6% silica C+6% calcite hydr. lime. For stabilizing.
D- sodium sesqui-silicate pentahydrate	$Na_3HSiO_4 . 5H_2O$		Less affected by aging than A, B, or E.
E- sodium ortho-silicate concentrated	Na_4SiO_4		At age 5 hrs. strength appeared independent of moisture.
		32	Does not improve the consistency properties once lime is the main stabilizing agent.
Silicon Dioxide	SiO_2	20	Increasing am'ts increase strength.

[c]Trade name for sodium tetraphosphate (P_2O_5-63.5%; Na_2O 36.0%; H_2O - 0.5%)

TABLE 3 (contd)

MISCELLANEOUS GROUP
(contd)

CHEMICAL ADDITIVES TO THE LIME-SOIL MIXES

Chemical	Formula	Reference	Remarks
Silicon Sesquioxide		20	Increasing amounts increase strength.
Sulfates		53	Does not respond well.
		56	Can lead to disintegration reaction with clay at high pH.
Vanadyl diChloride	$VOCl_2$	1	Note 1
Zinc Stearate		24	Increases weather resistance.

TABLE 4

Sources of Pozzolanic Materials

Reference	Source of Pozzolan: Artificial	Source of Pozzolan: Natural	Remarks
2E		Diatomaceous Shales Bentonite	Earths
16		Montmorillonite Kaolinite	
24	Fly-ash		1. Best if fine & low carbon content 2. When added to Montmorillonite & Kaolinite; not necessary for strength.
	Expanded shale		For gravels
39	Fly-ash	Volcanic ash	
	Expanded shales		Fines
58B		Clay mineral Quartz Feldspar Micas	
64	Scoria		1. Slaggy lava, dross 2. Typical mix; 4-7% lime & 10-15% pozzolan
	Cinders Slag	Chert	Water cooled
78B	Fly-ash Silica fume powdered brick burnt oil shale certain slags	certain clays opaline shales Diatomaceous earths cherts volcanic tuffs pumicites	

TABLE 5

Materials that Influence the Pozzolanic Reaction

Ref.	Activates	Other	Remarks
1	$NaOH$*		Incr. early strength. Holds pH high
	KOH*		" "
	$KHCO_3$		Incr. early strength
	Li_2CO_3		Best early strength acceleration
	Na_2CO_3*		Incr. early strength. Most promising tested. Powder form better than liquid.
	$NaHCO_3$		Incr. early strength
	$Na_2SO_3 \cdot 7H_2O$		"
	$KMnO_4$		Best overall strength increase
	$NaMnO_4 \cdot 3H_2O$		Best long term strength. Incr. early strength
	$Li_2SO_4 \cdot H_2O$		Incr. early strength
	LiF		Incr. early + long term strength
	$LiNO_3$		" "
	$NaNO_3$		" "
	$NaCl$		Promising, because it is cheap
	$CaCl_2$		Long term strength
	MgO*		Promising
	$MgCl_2 \cdot 4H_2O$		Long term strength
		CO_2(air)	Carbonation of lime stops pozzolan react.
		$AlCl_3$, $CuCl_2$, $FeCl_3$, $Fe_2(SO_4)_3 \cdot x\ H_2O$, $MgCl_2 \cdot 6H_2O$	May form weak bases and lower pH. May produce waterproofing effect.
64	Na_2CO_3MgO		Accelerates the high calcium limes. The reaction is sluggish when $Ca(OH)_2$ is used alone, but is accelerated by an equal amount of unhydrated MgO.
	Monohydrate		Proved more effective than the Dihydrate
	Dolomitic lime		Dolomitic lime.
	Quadrofos		Increases early strength.
		Sodium*** Montmorillonite	Ca^{++} could be depleted.
		Illite, Chlorite, Kaolinite****	Might be slightly pozzolanic.

*Apparent maximum beneficial concentration 0.5%.
**Strong oxidizing agent believed to oxidize the carbon in fly-ash K_2CO_3 or Na_2CO_3 and cause precipitation of MnO_2.
***Hindering effect.
****Only slight effect.

TABLE 6

Conditions Affecting the Pozzolanic Reaction

Ref	Condition	Remarks
1	Decrease pH/time	Presumably due to the lime being used up in the Pozz. reaction.
35	pH	Pozz. reaction proceeds rapidly because of increased solubility of silica at high pH.
36	pH* Nonplastic soils	Minimum pH 10.5 Generally a pozzolan is needed.
58B	Time*	Undesired carbonation and pozzolanic reactions are time dependent
	75°F* Higher temperature* Clay present*	Relatively slow reaction " fast " "It must be emphasized that a substantial quantity of clay must be present in the soil to provide an adequate source of silica and/or alumina for pozzolanic reaction."
	Soil properties Organic matter, pH , Soil weathering, & Soil drainage	Influences strength to varying degrees as a result of the lime-soil pozzolanic reaction
78B	Calcination*	To become active some pozzolans require calcination at 800°-2000°F and grinding to a fine size.

*Critical condition

TABLE 7

Types of Lime and Their Comparative Behavior

Refer.	Type	Other Names	Strength: lime% Low	Strength: lime% High	Strength: Water immersion A	Strength: Water immersion B	Strength: in general	Pozzolanic effect	Effectiveness Satisfactory 1	Effectiveness Satisfactory 2	Effectiveness Satisfactory 3	Hydration ease of	Chemical formula	Remarks
39, 41	QUICKLIME													Sensitive to soil moisture. 25% more CaO
24	Calcitic	Calcia										greater	CaO	
24	Dolomitic											lesser	CaO+MgO	
64	HYDRATED													Calcining temp. less critical
2A, 12 21, 24 39	Calcitic	high calcium	same	less	lower	no	lesser	lesser	no	yes	yes			
2A, 39 64	Dolomitic		same	greater			higher	greater						
12, 21 24, 64	Type N	normal hydrate monohydrate			higher	no	higher	best	yes				$Ca(OH)_2$ $+MgO$	
24, 64	Type S	pressure hydrated dihydrated					lesser	less					$Ca(OH)_2+$ $Mg(OH)_2$	

1. Base Course
2. Subbase
3. Subgrade
A. Montmorillonite and Illite soils
B. Kaolinite soils

BIBLIOGRAPHY

1. Davidson, D. T., Mateos, Manuel and Katti, R. K. "Activation of the Lime-Fly Ash Reaction by Trace Chemicals." HRB Bulletin 231 (1959).

2. McDowell, Chester

   A. "Properties of Lime for Soil Stabilization," Texas Highway Department Paper, TP-3-66-E (1966).

   B. "Evaluation of Soil-Lime Stabilization Mixtures," Texas Highway Department Paper, TP-2-65-E.

   C. "The Relation of Laboratory Testing to Design for Pavements and Structures on Expansive Soils," presented at the First Annual Soil Mechanics Conference of the Soil Mechanics and Foundations Div. Colorado Section of ASCE (Apr. 1959).

   D. "Development of Lime Stabilization," Texas Highway Department.

   E. "Stabilization of Soils with Lime, Lime-Fly Ash and other Lime Reactive Materials," HRB Lime & Lime-Fly Ash Soil Stabilization Committee. HRB Bulletin 231 (1959).

   F. "Recommended Lime Stabilization Practice," HRB Lime & Lime-Fly Ash Soil Stabilization Committee, (Report No. 1).

3. McDowell, Chester and Moore, W. H. "Improvement of Highway Subgrade and Flexible Bases by the use of Hydrated Lime," prepared for submission to Second International Conference on Soil Mechanics & Foundation Engineering.

4. Higgins, C. M. "High-Pressure Lime Injection," Louisiana Dept. of Highways R & D Section-BPR Research Report No. 17, Interim Report No. 2, Research Project No. 63-7S.

5. Brand, W. and Schoenberg "Impact of Stabilization of Loess with Quicklime on Highway Construction," HRB Bulletin 231 (1959).

6. Williams, W. W. and Handy, R. L. "Chemical Stabilization of an Active Landslide, The Aurora Avenue Landslide," presented at the 17th Annual Highway Geology Symposium.

7. Boynton, Robert S. "Specifications for and Techniques of Construction of Lime Stabilized Courses," presented at AASHO, Atlanta, Georgia on Dec. 10, 1964.

8. Davidson, S. E. and Page, J. B. — "Factors Influencing Swelling and Shrinking in Soils," presented before Division 1 Soil Science Society of America, Davis, Calif. (Aug. 1955).

9. Larsen, Melvin B. — "Stabilization of Soils and Surfaces by use of Various Stabilizing Agents on Iowa Secondary Roads," presented at AASHO in Atlanta, Georgia, Dec. 10, 1964.

10. Greenberg, Sidney A. — "The Chemical Reaction of Calcium Hydroxide, Silica and Water Mixtures at 82°," Jr. of Physical Chemistry, Vol. 61.

11. Diamond, Sidney — "Rapid Reaction of Lime with Hydrous Alumina," Nature (England) No. 4954, Vol. 204 (1964).

12. Davison, D. T. Mateos, Manuel, and Barnes, H. F. — "Improvement of Lime Stabilization of Montmorillonitic Clay Soils with Chemical Additives," HRB Bulletin 262 (1960).

13. Eades, James L. and Grim, Ralph E. — "Reaction of Hydrated Lime with Pure Clay Minerals in Soil Stabilization", HRB Bull. 262 (1960).

14. Ladd, C. C., Moh, Z. C., and Lambe, T. W. — "Recent Soil-Lime Research at the Massachusetts Institute of Technology," HRB Bulletin 262 (1960).

15. Taylor, W. H., Jr. and Arman, Ara — "Lime Stabilization using Preconditioned Soils," HRB Bulletin 262 (1960).

16. Hilt, G. Harrison and Davidson, D. T. — A. "Lime Fixation in Clayey Soils," HRB Bulletin 262 (1960).
B. "Isolation and Investigation of a Lime-Montmorillonite Crystalline Reaction Product," HRB Bulletin 304 (1961).

17. Anday, M. C. — "Accelerated Curing for Lime-Stabilized Soils," HRB Bulletin 304 (1961).

18. Mitchell, J. K. and Hooper, D. R. — "Influence of Time between Mixing and Compaction on Properties of a Lime-Stabilized Expansive Clay," HRB Bulletin 304 (1961).

19. Mateos, Manuel and Davidson, Donald T. — "Further Evaluation of Promising Chemical Additives for Accelerating Hardening of Soil-Lime-Fly Ash Mixture," HRB Bulletin 304 (1961).

20. Wang, Jerry Wen-Hann, Davidson, Donalt T., and Rosauer, Elmer A. — "Comparison of Various Commercial Limes for Soil Stabilization," HRB Bulletin 335 (1962).

21. Remus, Melvyn D.
Davidson, D. T.
"Retention of Strength Composition and Density of Lime-Treated Clayey Soils," HRB Bulletin 304 (1961).

22. Ruff, Clarence G. and
Davidson, Donald T.
"Lime and Sodium Silicate Stabilization of Montmorillonite Clay Soil," HRB Bulletin 304 (1961).

23. Dawson, Raymond F. and
McDowell, Chester
"A Study of an Old Lime-Stabilized Gravel Base," HRB Bulletin 304 (1961).

24. Herrin, Moreland and
Mitchell, Henry
"Lime-Soil Mixtures," HRB Bulleting 304 (1961).

25. Miller, Richard H. and
Couturier, Robert R.
"An Evaluation of Gravels for Use in Lime-Fly Ash-Aggregate Composition," HRB Bulletin 304 (1961).

26. Gutschick, Kenneth A.
"Altering Physico-Chemical Characteristics of Clay-Bearing Soils with Lime," Proceedings of the 12th Annual Symposium on Geology as Applied to Highway Engineering, Univ. of Tennessee Engineering Experiment Station, Bulletin 24 (1961).

27. Kaffi, R. K. and
Barve, A. G.
"Effect of Inorganic Chemicals on the Consistency Properties of an Expansive Soil Sample," HRB Bulletin 349 (1962).

28. Sheeler, J. G.
Picaut, J. G., and
Demirel, T.
"Electrical Resistivity of Soil-Sodium Chloride Systems," HRB Bulletin 349 (1962).

29. Tumay, M. T.
Larew, H. G., and
Meem, J. L.
"Effects of Neutron-Gamma Irradiation on Physico-Chemical Properties of Fine-Grained Soils," HRB Bulletin 349 (1962).

30. Laguros, J. G.,
Handy, Richard L., and
Reign, Lewis L.
"Effect of Exchangeable Calcium on Montmorillonite Low-Temperature Endotherm and Basal Spacing," HRB Bulletin 349 (1962).

31. Walker, Richard D. and
Karabulut, Cetin
"Effect of Freezing and Thawing on Unconfined Compressive Strength of Lime Stabilized Soil," HRR 92 (1964 and 1965).

32. Laguros, J. G.
"Lime-Stabilized Soil Properties and the Beam Action Hypothesis," HRR 92 (1964 and 1965).

33. Hoover, J. M.
"Evaluation of Experimental Stabilized Soil Base Construction, Webster Co., Iowa," HRR 92 (1964 and 1965).

34. Thomas, C. E.,
Jones, W. G., and
Davis, W. C.
"Lime and Phosphoric Acid Stabilization in Missouri," HRR 92 (1964 and 1965).

35. Diamond, Sidney and Kinter, Earl B. — "Mechanisms of Soil-Lime Stabilization," HRR 92 (1964 and 1965).

36. Davidson, L. K., Demirel, T. and Handy, R. L. — "Soil Pulverization and Lime Migration in Soil-Lime Stabilization," HRR 92 (1964 and 1965).

37. Taylor, W. H., Jr. — "Stabilizing Organic Fills with Lime in Louisiana," American Road Builders' Association, Technical Bulletin No. 233 (1957).

38. Arman, Ara and Saifan, Fayez Sail — "The Effect of Delayed Compaction on Stabilized Soil," Cement Engineering Research Bulletin No. 88 (1965).

39. American Road Builders Association — "Lime Stabilization Construction Manual," Technical Bulletin No. 243 (1957).

40. Berkland, James O. — "Swelling Vermiculite Clay in the Franciscan Formation of Northern California - Its Role in Possible Chemical Stabilization of Mobile Slopes," presented to the National Convention of the Association of Engineering Geologists, Sacramento, Calif. Oct. 30, 1964.

41. U.S. Department of Commerce — "Soil Stabilization (Investigation of Quicklime as a Stabilizing Material)," AD 402304, U.S. Army Corps of Engineers, Technical Report No. 3-455, Report 5, (March, 1962).

42. Cross, Bruce — "Liquid Gas Freezes Bad Soil," <u>Construction Methods and Equipment</u>, Vol. 46, No. 7 (July 1964).

43. Puzinauskas, V.P. and Kallas, B. K. — "Stabilization of Fine-Grained Soils with Cutback Asphalt and Secondary Additives," HRB Bulletin 309 (1961).

44. Zolkov, Elias — "Influence of Chlorides and Hydroxides of Calcium and Sodium on Consistency Limits of a Fat Clay," HRB Bulletin 309 (1961).

45. McBain, James W. — <u>Colloid Science</u>, D. C. Heath & Co. (1950).

46. Glenn, George R. and Handy, R. L. — "Lime-Clay Mineral Reaction Products," presented at the 42nd Annual Meeting of HRB Jan. 1963 - Special Report.

47. Cleaves, Arthur B. — <u>Landslide Investigations - A Field Handbook for Use in Highway Location and Design</u>, U.S. Department of Commerce, Bureau of Public Roads (1961).

48. Eckel, Edwin B., ed. — "Landslides and Engineering Practice," NAS-NRC Pub. 544, HRB Special Report 29 (1958).

Root, Arthur W. — A. Prevention of Landslides

Baker, Robert F. and Marshall, Harry E. — B. Control and Correction

49. McNeal, Brian L. — "Effect of Exchangeable Cations on Glycol Retention by Clay Minerals," U.S. Department of Agriculture (1963).

50. Norton, F. H. — Elements of Ceramics, Adison Wesley Press, Inc. (1952).

51. Peck, Ralph B. Hanson, Walter E. and Thornburn, Thomas H. — Foundation Engineering, John Wiley & Son, Inc. (1965).

52. Engineering News-Record

A. "Love Field Runway: Lime, Cement, Concrete, Steel," Vol. 173, No. 13 (Sept. 24, 1964).

B. "Grout Curtain Under Swiss Dam Costs $5 Million," Vol. 173, No. 22 (Nov. 26, 1964).

53. Zube, Ernest, Gates, Clyde, and Hatano, Mas — "Interim Report on Effects of Hydrated Lime in Treating Soils," Calif. Division of Highways, Materials & Research (1965).

54. Zube, Ernest and Gates, Clyde — "California's Experience with Lime Treatment in Road Construction," California Highways and Public Works, (January-February 1966).

55. Dumbleton, M. J. — "Lime-Stabilized Soil for Road Construction in Great Britain - A Laboratory Investigation." Roads and Road Construction, 40 (479), 321/325 (November 1962).

56. Sherwood, P. T. — "The Effect of Sulfates on Cement- and Lime-Stabilized Soils," Roads and Road Construction 40 (470) 34/40 (February 1962).

57. Pacific Road Builder and Engineering Review — "Lime Soil Stabilization," Vol. 107 No. 2 (August 1965).

58. Thompson, Marshall R.

A. "The Significance of Soil Properties in Lime-Soil Stabilization," Highway Engineering Series No. 13, Illinois Cooperative Highway Research Program Series No. 2, Project IHR-76, University of Illinois, The State of Illinois Division of Highways and The U.S. Dept. of Commerce, BPR (1964).

B. "Influence of Soil Properties on Lime-Soil Reactions," Public Works (Aug. 1965).

59. The 1963 Street and Highway Manual and Catalog File — "Stabilization and Aggregates."

60. Riha, Brydon — "Decisive Factors Concerning Lime Treatment of Soil in Urban Areas," presented before Eighth Annual Highway & Public Works Conference, March 1965, Univ. of the Pacific, Stockton, Calif.

61. Kleinfelder, James H. — "Stabilization of Clay Soils," presented before Eighth Annual Highway & Public Works Conference, March 1965, Univ. of the Pacific, Stockton, Calif.

62. White, Eliot J., Baptist, Oren C. and Land, Carlon S. — "Physical Properties & Clay Mineral Content Affecting Susceptibility of Oil Sands to Water Damage, Powder River Basin, Wyo." U.S. Dept. of the Interior, Bureau of Mines report of investigation 6093 (1962).

63. Russam, K. and Dumbleton, M. J. — "The Nature & Properties of the Subgrade Soil at Melbourn Airport," Austral. Road Res. B.D. Proc., Vol. 2, Part 2, Paper No. 186.

64. Woods, Kenneth B., Berry, Donald S., and Goetz, William — Highway Engineering Handbook - First Edition McGraw-Hill Book Co. (1960).

65. Corps of Engineers U.S. Army Manual — Soil Stabilization for Roads and Streets, EM 1110-345-304 (31 Jul 61).

66. Engineering (Great Britain). — "Tobermorite Gel-The Heart of Concrete," Vol. 194, No. 5024 (Aug. 3, 1962).

67. Chemical Abstracts — "Lime potential and degree of base saturation of soils," V. 63, No. 73, 1179 (July 1965).

68. Brewer, Roy — "Fabric and Mineral Analysis of Soils," John Wiley and Son, Inc. (1964).

69. Iwamoto, Shigeki and Sudo, Toshio — "Chemical Reactions Among Clays Minerals, Calcium Carbonate, and Ammonium Chloride," The American Mineralogist, V. 50, (July-Aug. 1965).

70. Sridhara, S. — "Soil-Lime Research at Iowa State University," (Discussions), Journal of the Soil Mechanics and Foundations Division-ASCE Proceedings, p. 223, V 90, No. SM6, (Nov. 1964).

71. Kumbasar, Vahit and Togrol, Ergun — "Soil-Lime Research at Iowa State University," (Discussions), Journal of the Soil Mechanics and Foundations Division - ASCE Proceedings, p. 224, V 90, No. SM6, (Nov. 1964).

72.	Nagaraj, T. S.	"Soil-Lime Research at Iowa State University," (Discussion) Journal of the Soil Mechanics and Foundations Division-ASCE Proceedings, p. 225, V. 91, No. SM6 (Nov. 1964).
73.	Mateos, Manual	"Soil-Lime Research at Iowa State University," (closure) Journal of the Soil Mechanics and Foundations Division-ASCE Proceedings, p. 129, V. 91, No. SM3 (1965).
74.	Roth, Lloyd B.	"Post-Stabilization With Lime," Rural and Urban Roads, p. 71, (Dec. 1965).
75.	Roads & Streets Magazine	"Lime Corrects Bad-Acting Clay for Airport Extension," p. 82, (October 1962).
76.	Litvinov, I. M.	"Stabilization of Settling and Weak Clayey Soils by Thermal Treatment," Soil and Foundation Engineering in the Union of Soviet Socialist Republics, p. 94, HRB Special Report 60.
77.	Lambe, William T.	"Soil Stabilization," Soil and Foundation Engineering in the Union of Soviet Socialist Republics, p. 172, HRB Special Report 60.
78.	Urquhart, Leonard Church, ed.	Civil Engineering Handbook, McGraw-Hill, Fourth Edition, (1962).
	Babbitt, Harold E.	A. "Water Supply and Treatment."
	Gilkey, Herbert J.	B. "Cement and Concrete."
79.	Wissa, Anwar E. Z. and Halaby, Rurik	"Chemical Stabilization of Selected Tropical Soils from Puerto Rico and Panama," U. S. Army Engineer Waterway Experiment Station, Vicksburg, Mississippi. M.I.T. Phase Report No. 4, Soils Pub. No. 160, Oct. 1964.